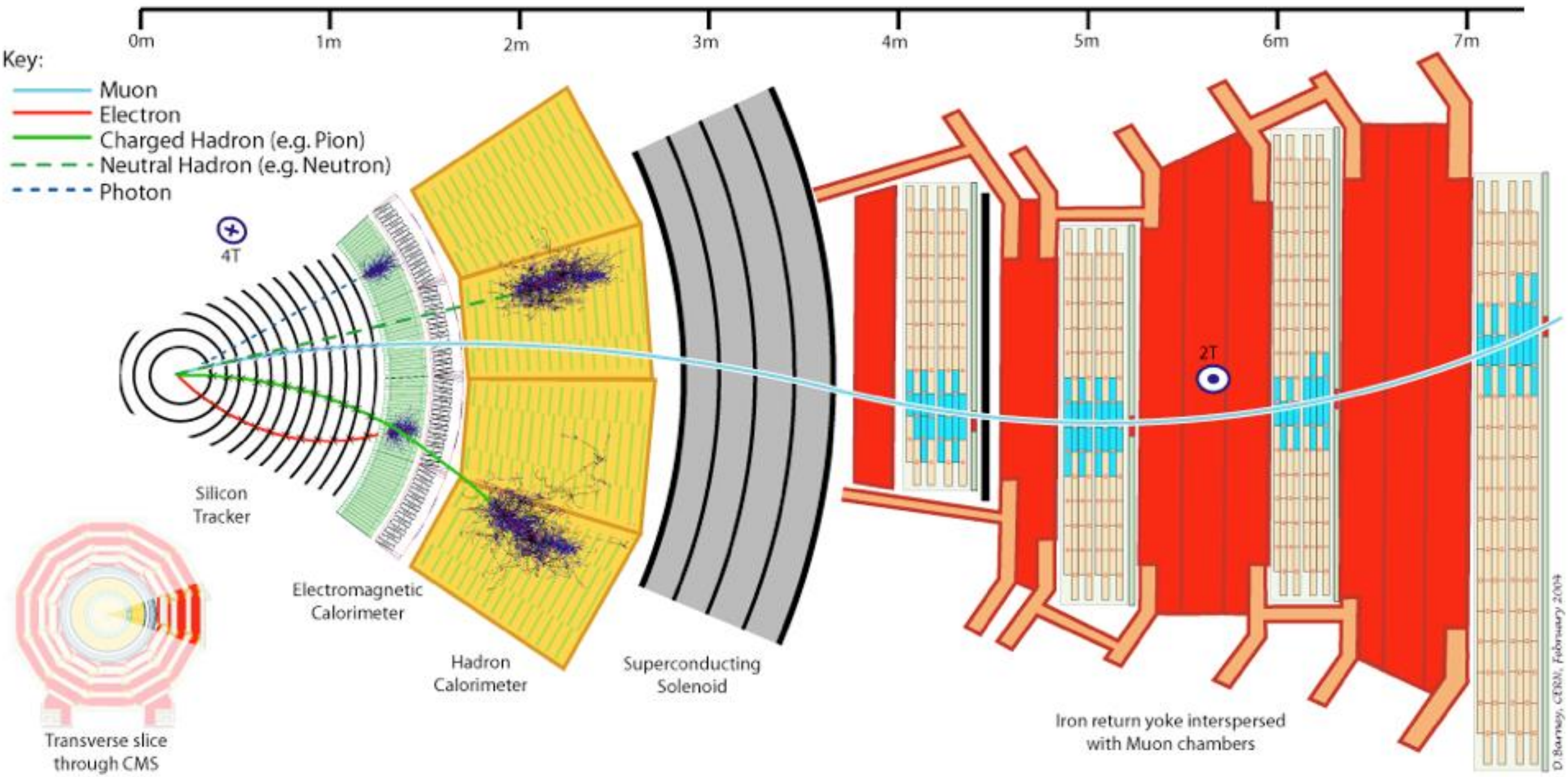
Jet Reconstruction Using Particle Flow in Heavy-Ion Collisions in CMS

Yen-Jie Lee (MIT)

sPHENIX Jet Structure Meeting

The CMS Detector

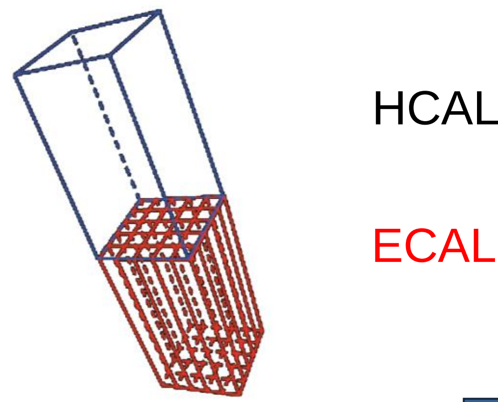
Primary sub-detectors: Silicon tracker, ECAL, HCAL, muon chambers

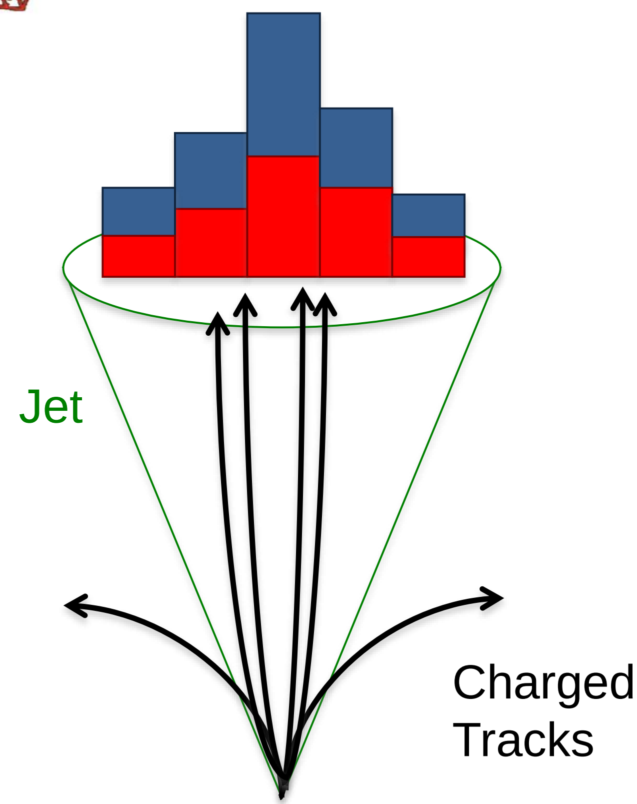


CMS can distinguish stable particles as: $h^{+/-}$, γ, h^0, μ, e

Calorimeter Jets

- "Traditional" jet reconstruction
- Calorimeter Towers
  - 1 HCAL cell ~ 0.085 (Δη x Δη)
  - 25 ECAL crystals ~ 0.017 (Δφ x Δη)
- Does not make use of ECAL granularity
- Jet resolution driven by HCAL:
  - HCAL resolution ~ 110%/√E
  - non-compensating → non-linear response
- Low p_T charged hadrons bent outside jet



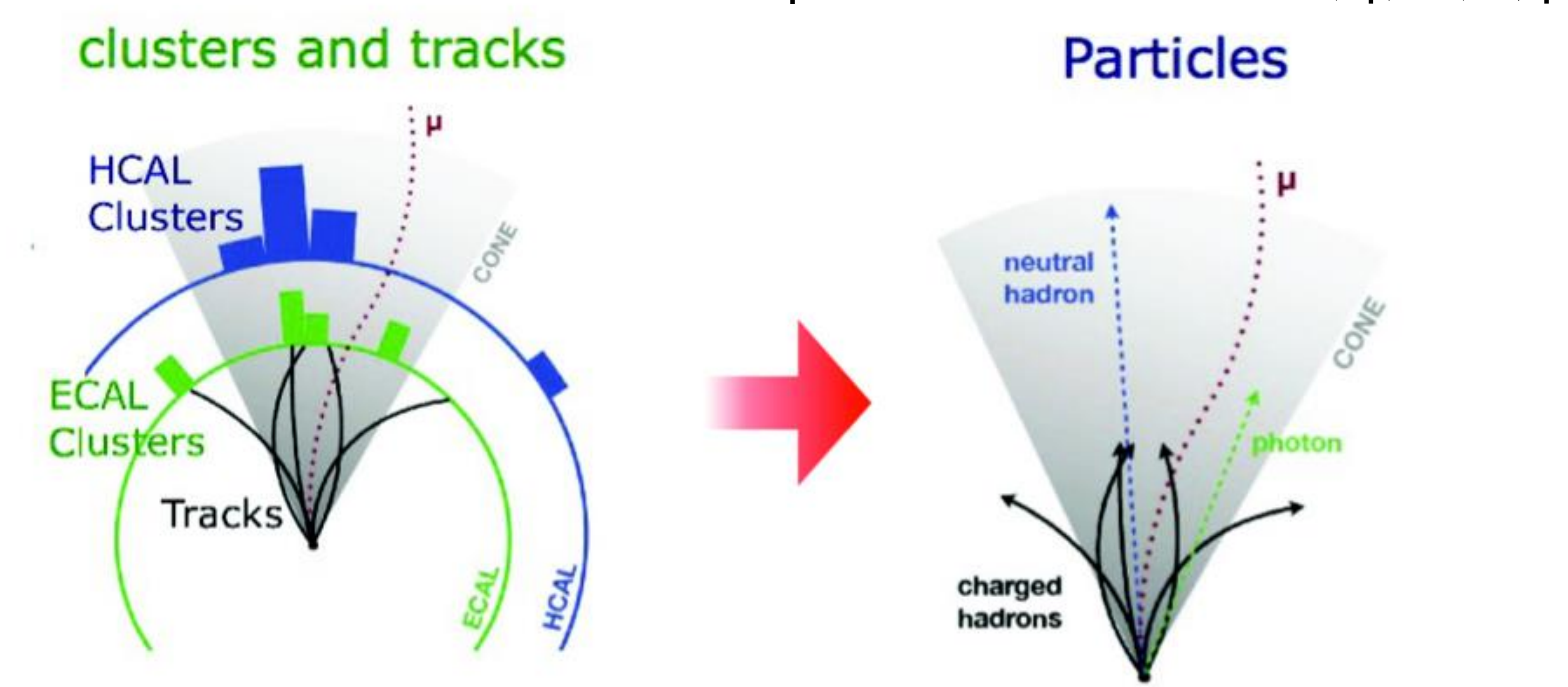


Purely calorimetric jet reconstruction does not take advantage of the full versatility of CMS

What is Particle Flow?

Hint: It's got nothing to do with hydrodynamics

Particle flow reconstructs all stable particle in the event: $h^{+/-}$, γ, h^0, e, μ

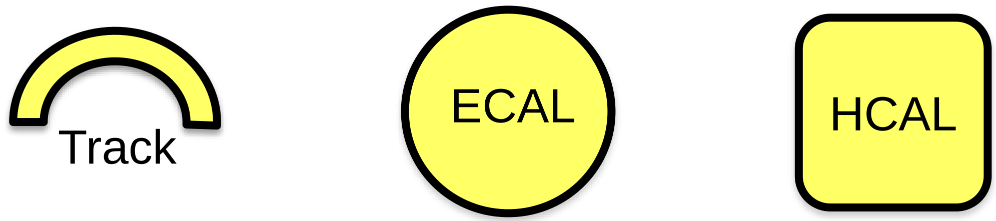


- On average jets are:

  ~ 65% charged hadrons, ~ 25% photons, ~ 10 % neutral hadrons
- Using the silicon tracker (vs. HCAL) to measure charged hadrons
  - Improves resolution, avoids non-linearity
  - Decreases sensitivity to the fragmentation pattern of jets
- Used extensively in ALEPH, CMS and proposed for the ILC

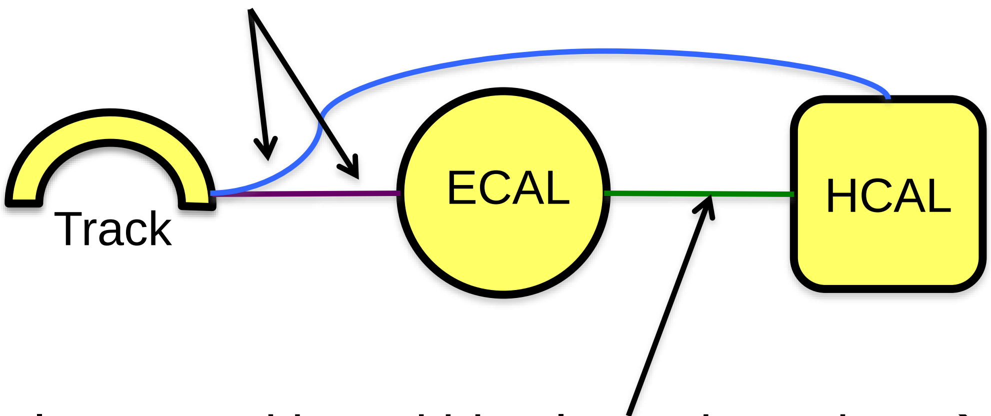
The PF Recipe

1. Reconstruct *elements*: tracks, calorimeter clusters, muon tracks



The PF Recipe

1. Reconstruct *elements*: tracks, calorimeter clusters, muon tracks
2. Elements are *linked* into *blocks*
   - Track trajectory intersects calorimeter cluster boundary → Link

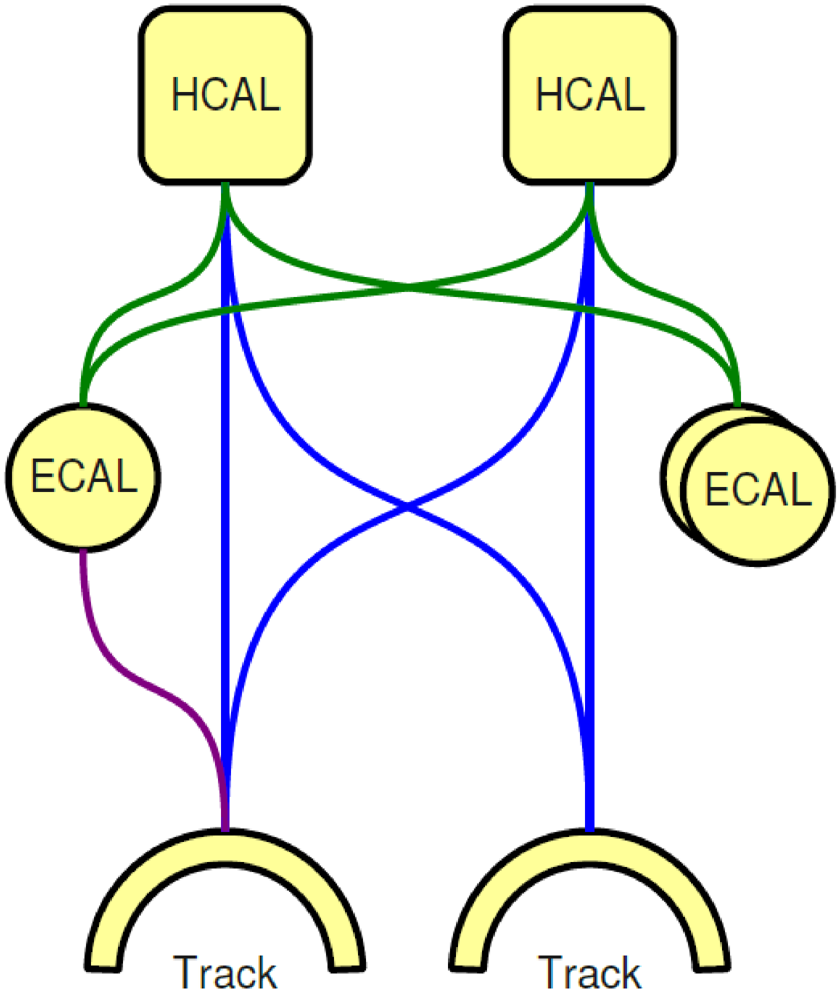


   - ECAL cluster position within cluster boundary → Link
3. *Reduce* blocks into particle candidates (next slides)
4. Use particle candidates to reconstruct higher level objects:

   jets, missing E_T, taus, …

From Blocks to Particles

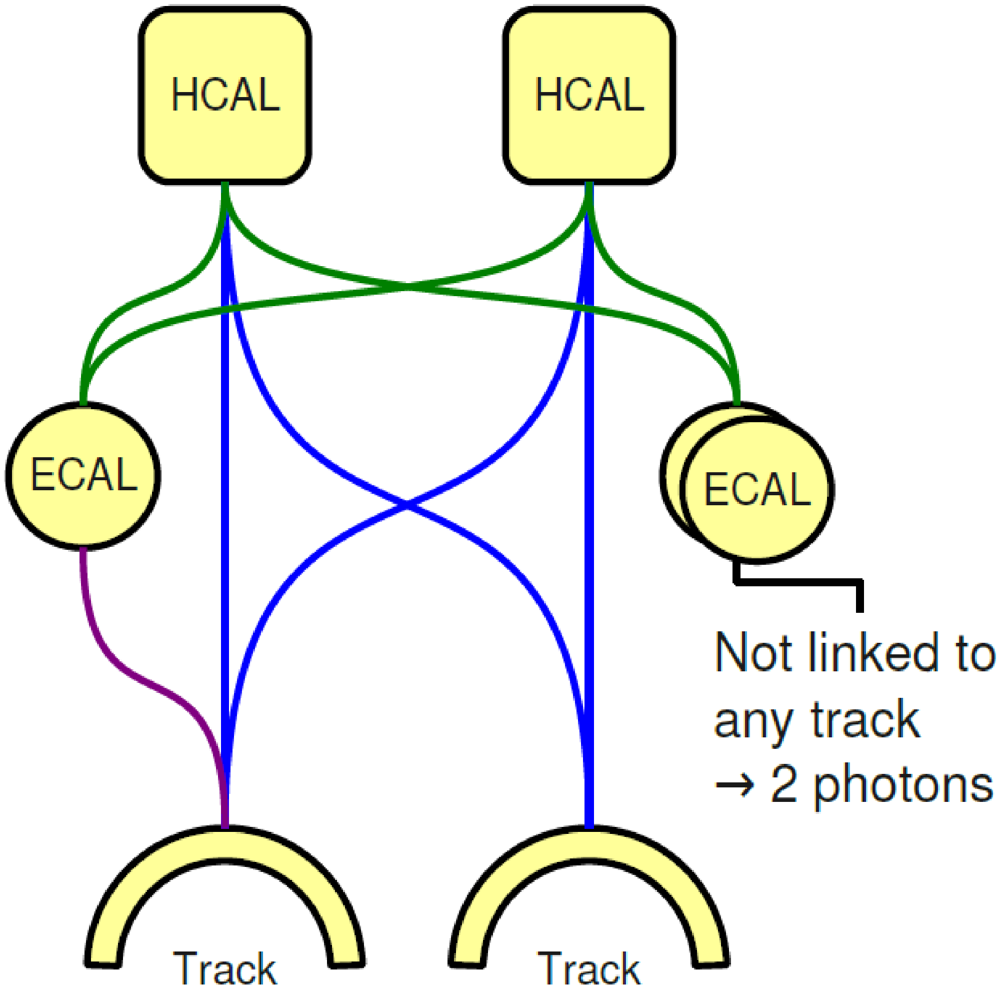
Blocks may be composed of several elements



How to reduce blocks into particles?

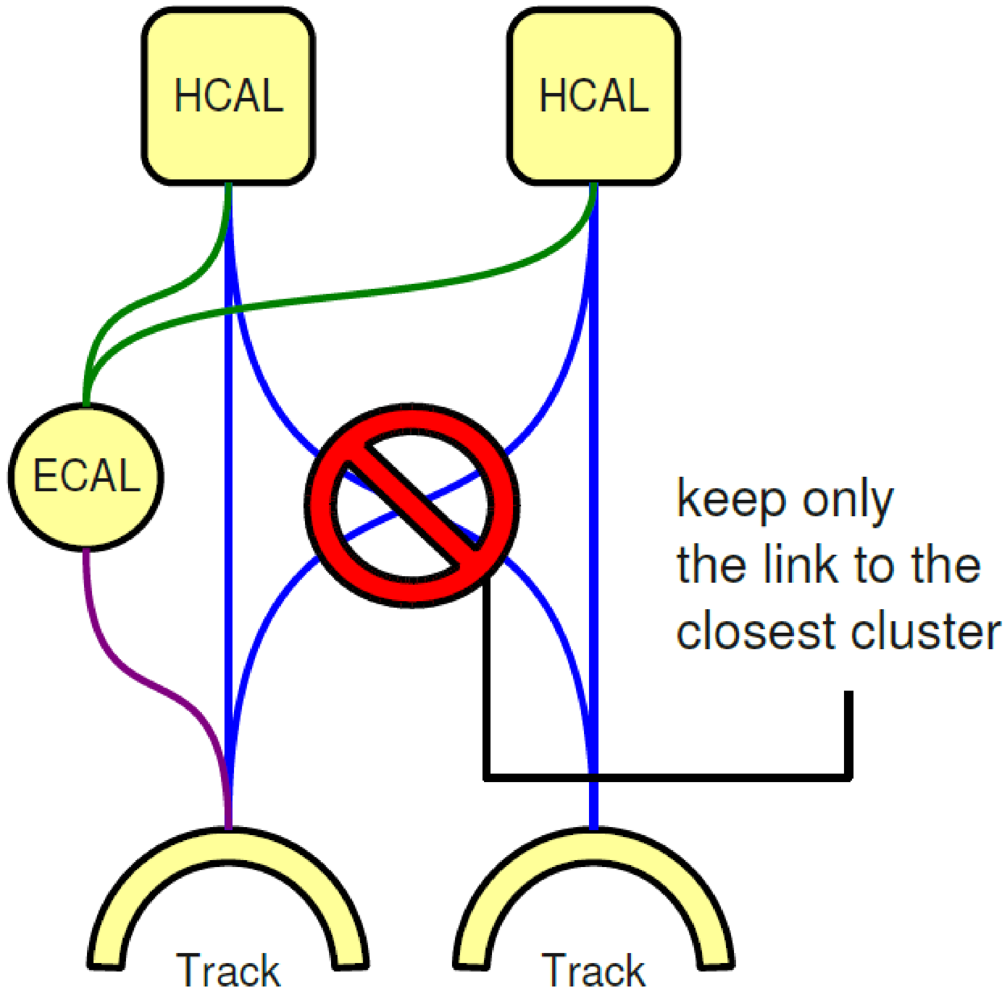
From Blocks to Particles

ECAL clusters not linked to any track are likely photons

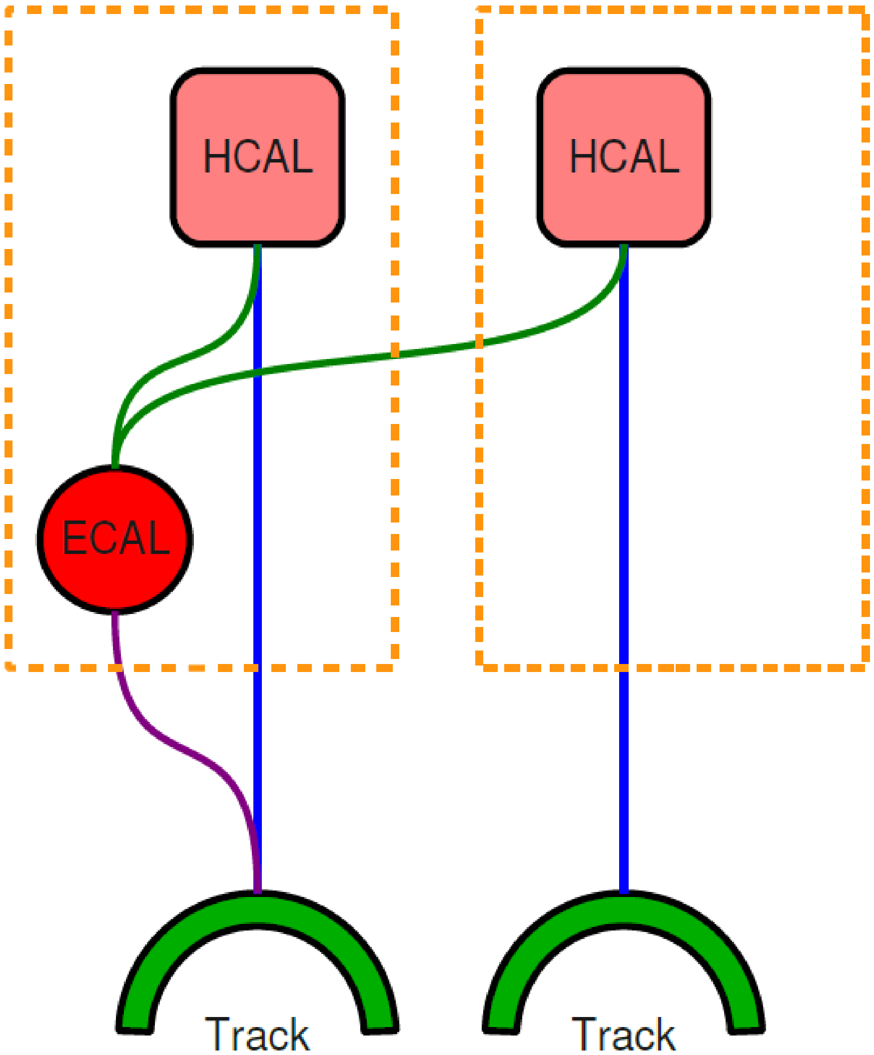


From Blocks to Particles

Each charged hadron should contribute only one track



Charged Hadrons

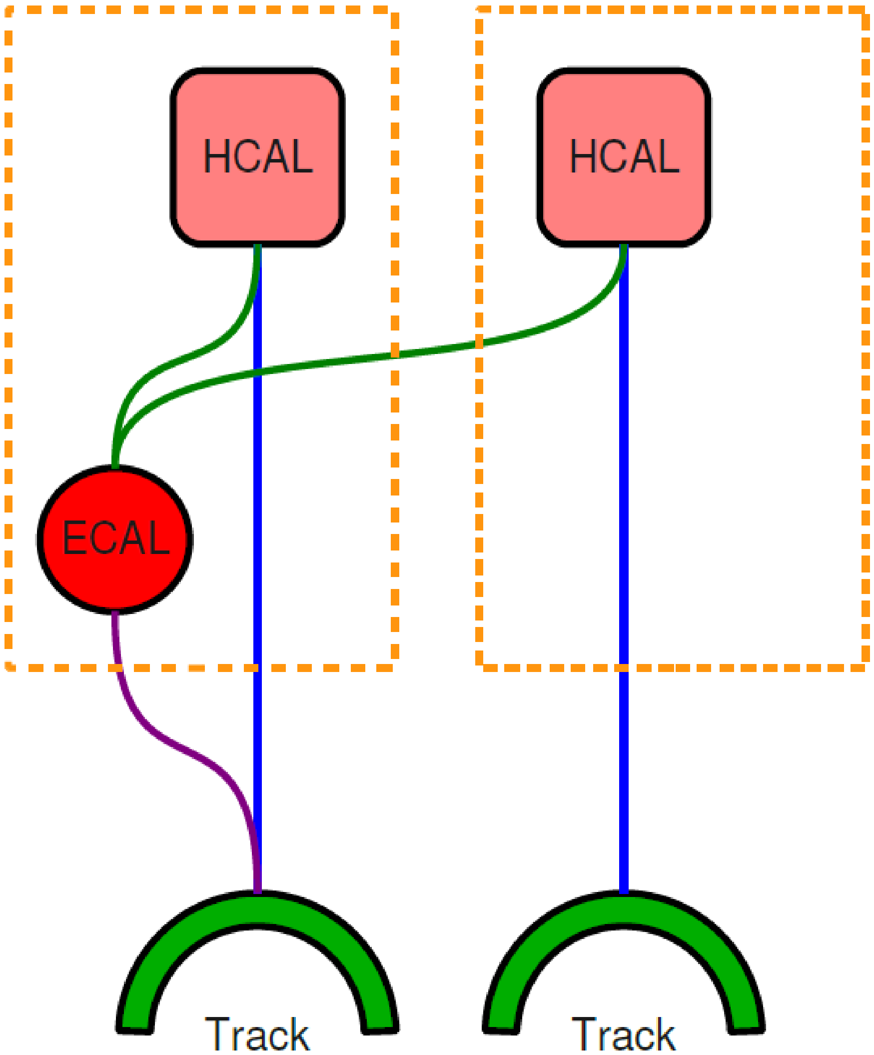


- Test the remaining elements for compatibility with charged hadron hypothesis
- For each HCAL cluster, compare:
  - Sum of linked track momenta, *p*
  - Sum of linked calorimeter cluster energy, *E*
- Calorimeter energy is calibrated to the response of charged hadrons

$$E = a + b\, E_{ECAL} + c\, E_{HCAL}$$

- If E < p + 1.2 * √p, charged hadrons are created (and nothing else)
- Momentum assigned is a weighted average of calorimeter and track information

Overlapping Showers



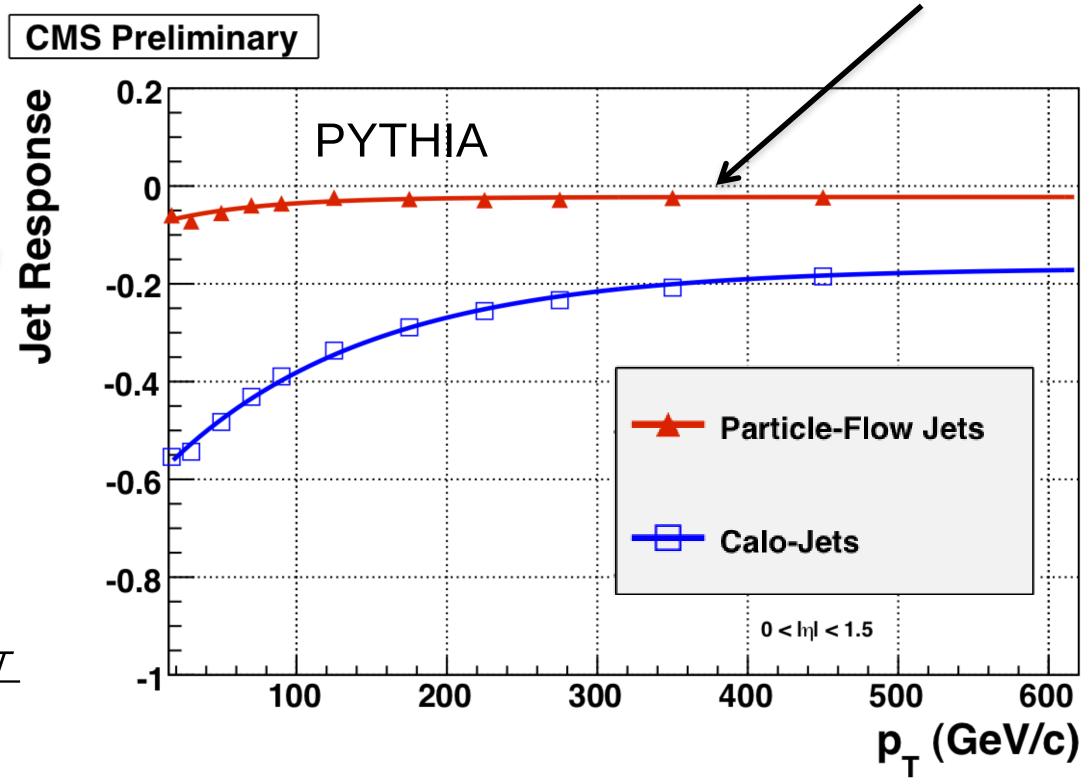
- If $E > p + 1.2 * \sqrt{p}$ then neutral particles are also created
- If the excess (E - p) comes only from:
  - HCAL → h^0 $(E - p)$
  - ECAL → γ $(E_{ECAL} - p/b)$
- If excess from both ECAL and HCAL:
  - $E_{ECAL} > E - p$ → γ $\left(\frac{E - p}{b}\right)$
  - $E_{ECAL} < E - p$ → γ (E_{ECAL})

    h^0 (remainder)
- Photon production given precedence

Performance of PF Jets in pp

CMS-PAS-PFT-09-001

PF reconstructs > 95% of the jet p_T



Barrel: $|\eta| < 1.5$

Mean of Gaussian fit to

$$\frac{Reco\ p_T - Gen\ p_T}{Gen\ p_T}$$

Generator-level

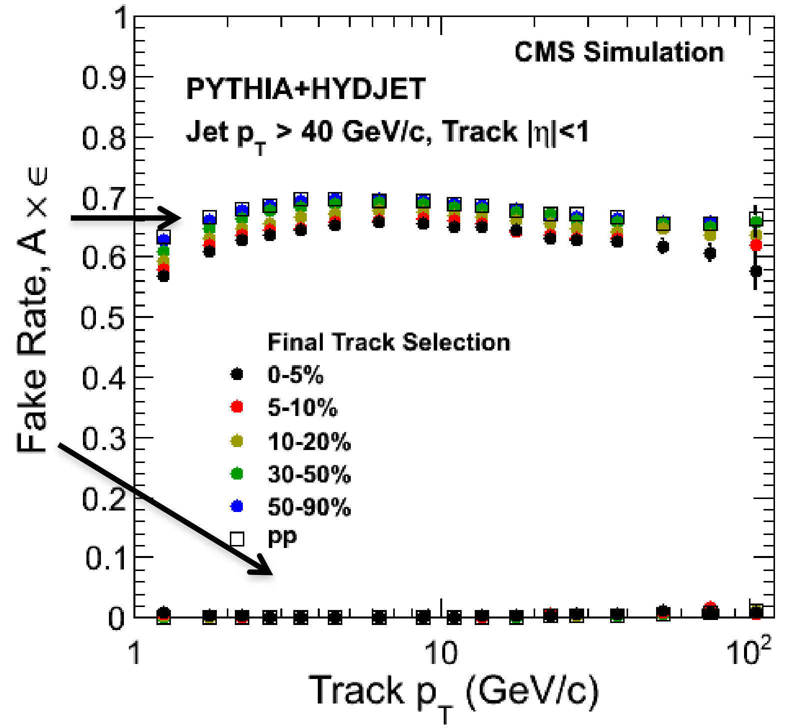
Better response w.r.t. calorimeter measurement
→ smaller jet-energy corrections

Particle Flow Jets in PbPb Collisions

- Same PF algorithm as pp except
  - No PF electron reconstruction (yet)
  - Different tracking algorithm
- Hadrons with no reconstructed track default to calorimeter measurement
- Jet reconstruction in heavy ions:

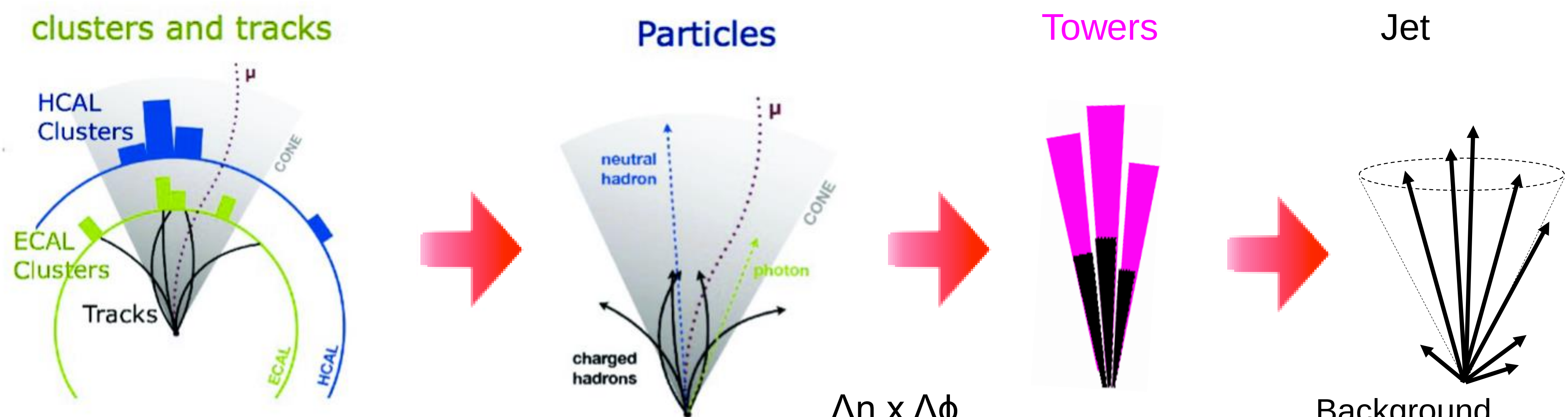
1. Event-by-event subtraction of the heavy-ion background (next slide)
2. Jet energy corrections (JEC) based on GEANT simulation of PYTHIA jets
3. Validation of the BG subtraction + JEC for PYTHIA jets embedded in HYDJET

PbPb Tracking Performance



pp algorithm ~ 90% efficiency

Jet Reconstruction and Composition



$\Delta\eta$ x $\Delta\phi$
0.076 x 0.076 in barrel

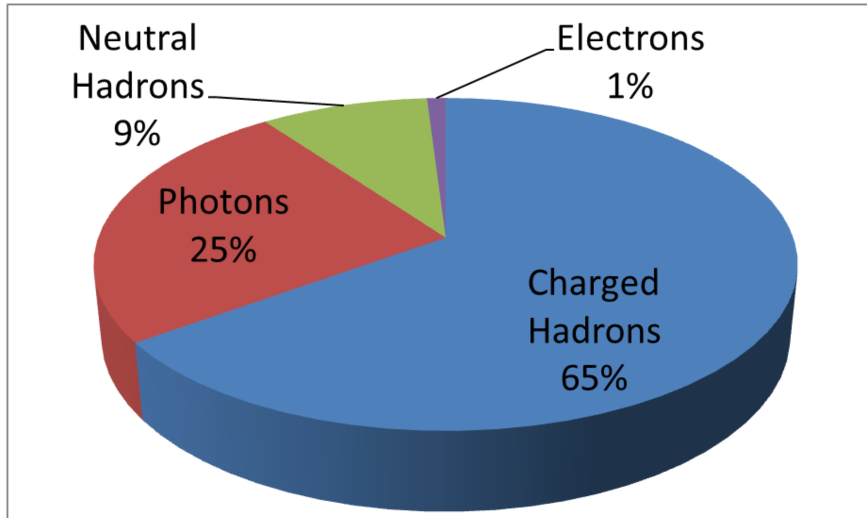
Background subtraction and jet clustering

Anti-k_T algorithm is used in most CMS publication

On average, charged hadrons carry 65% of the jet momentum

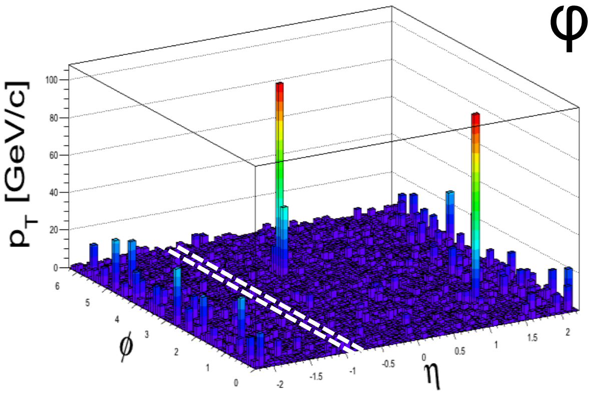
Measure the known part
Correct the rest by MC simulation

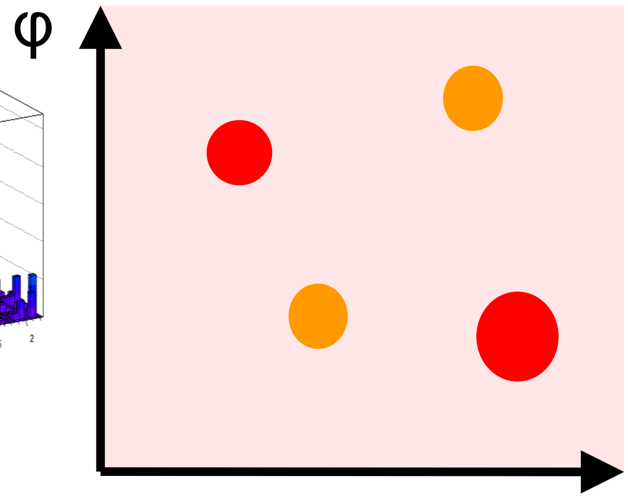
Optimize the use of calorimeter and tracker
Example: “Particle Flow” in CMS

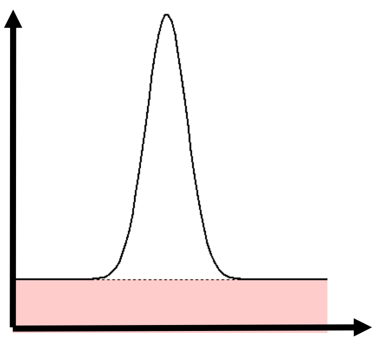


A typical high p_T jet

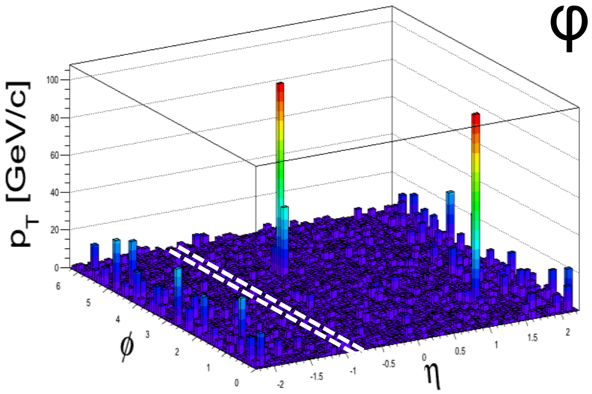
Background Subtraction

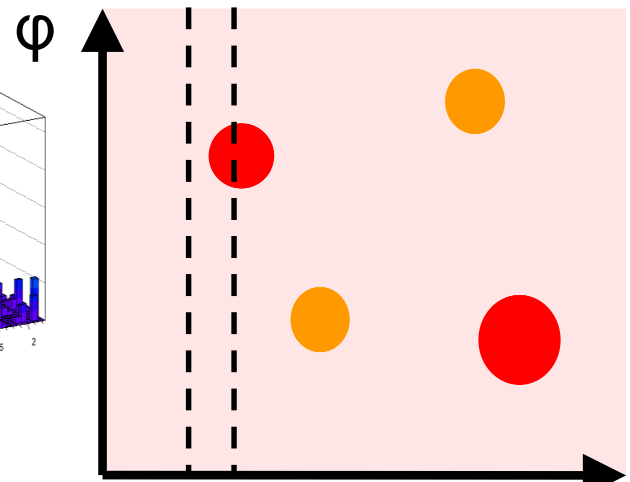




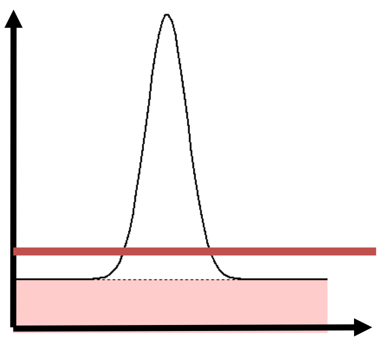


Background Subtraction





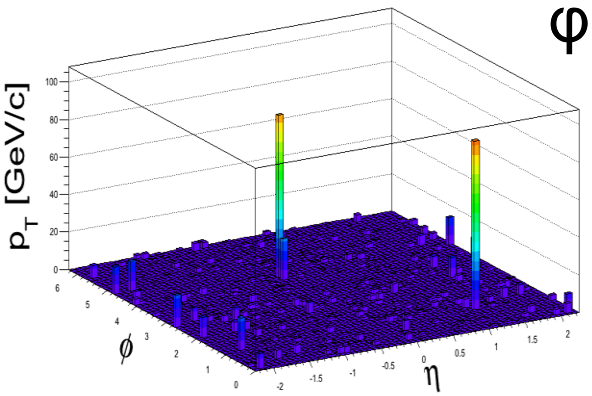
1. Background energy per tower calculated in strips of η. Pedestal subtraction

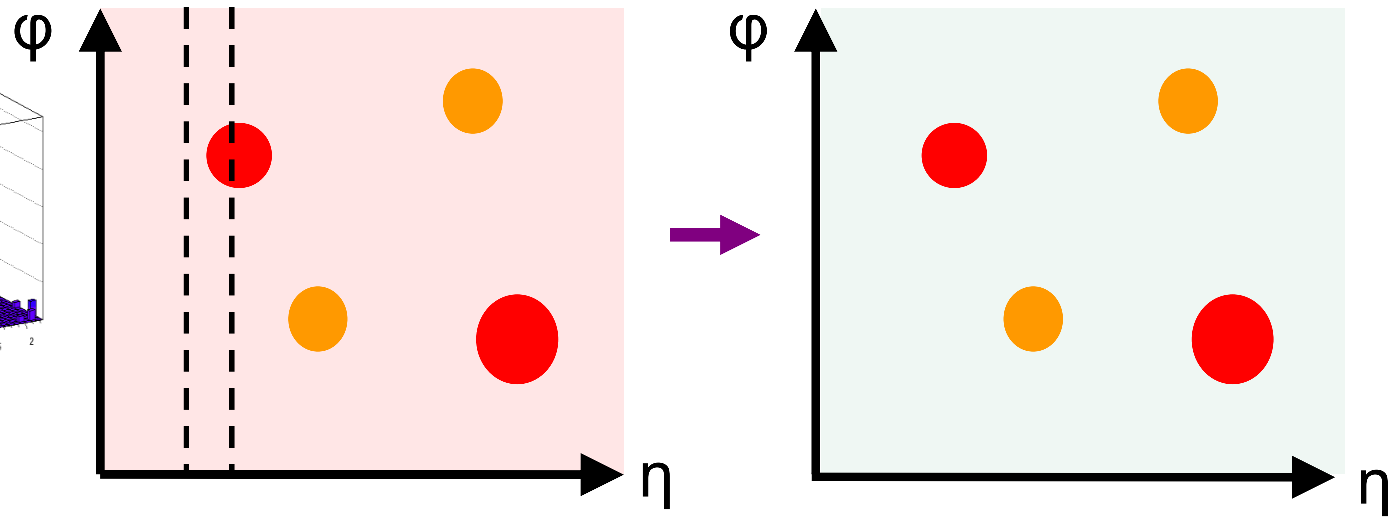


Background level

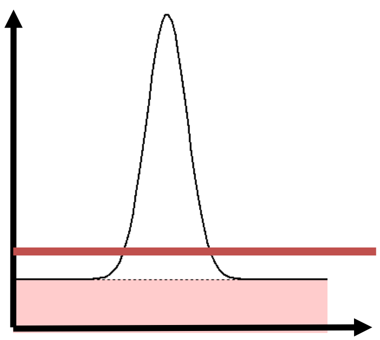
Estimate background
for each tower ring of constant η
estimated background = $\langle p_T \rangle + \sigma(p_T)$
- Captures dN/dη of background
- Misses ϕ modulation – to be improved

Background Subtraction



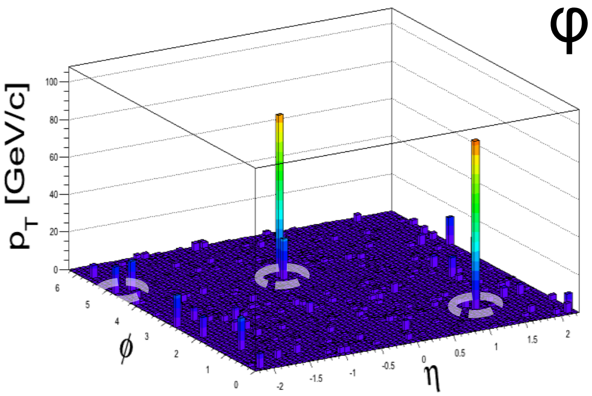


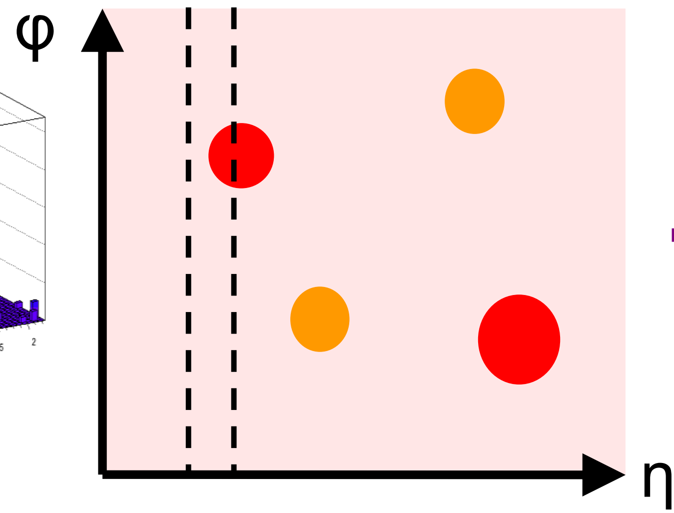
1. Background energy per tower calculated in strips of η. Pedestal subtraction



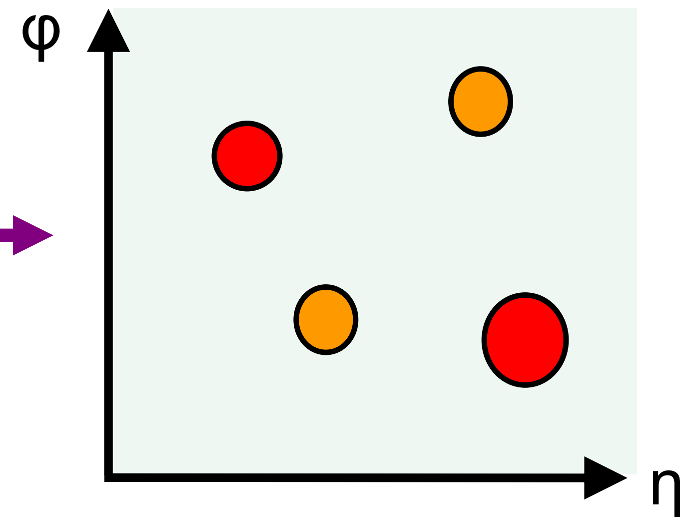
Background level

Background Subtraction

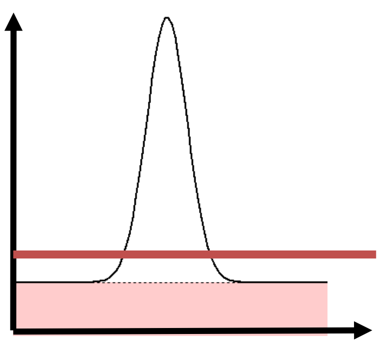




1. Background energy per tower calculated in strips of η. Pedestal subtraction

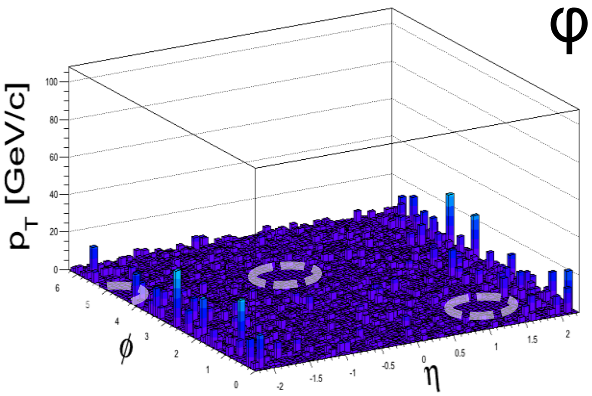


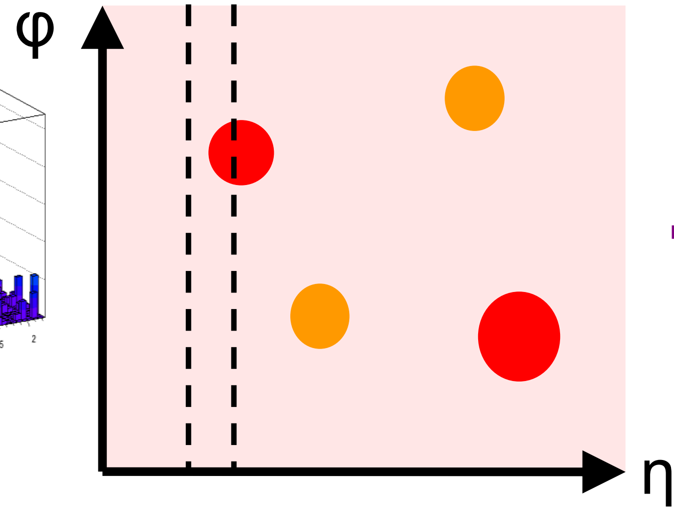
2. Run anti k_T algorithm on background subtracted towers



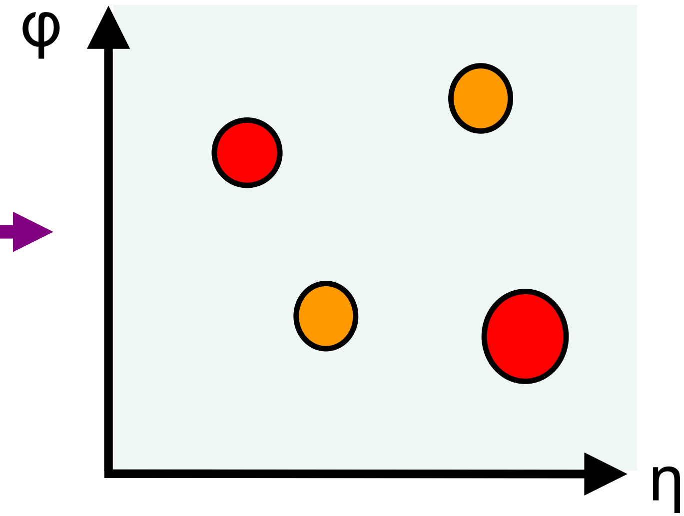
Background level

Background Subtraction

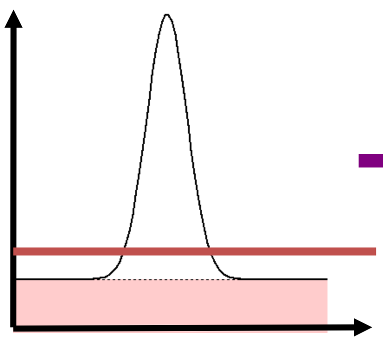




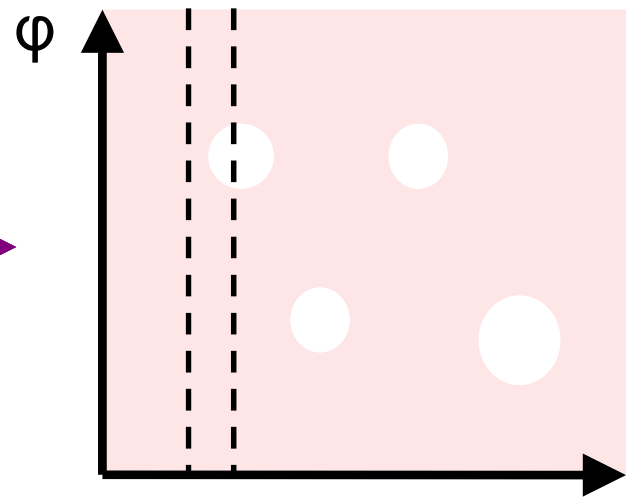
1. Background energy per tower calculated in strips of η. Pedestal subtraction



2. Run anti k_T algorithm on background subtracted towers

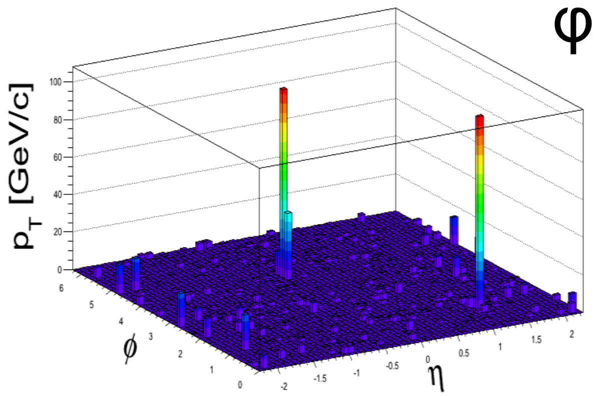


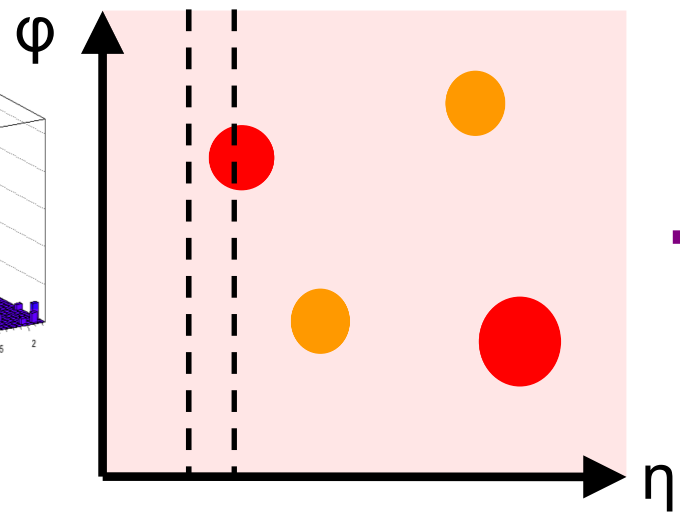
Background level



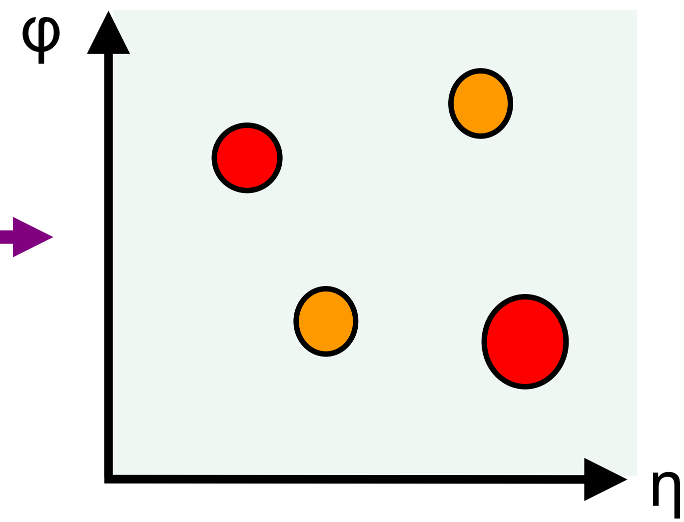
3. Exclude reconstructed jets

Background Subtraction

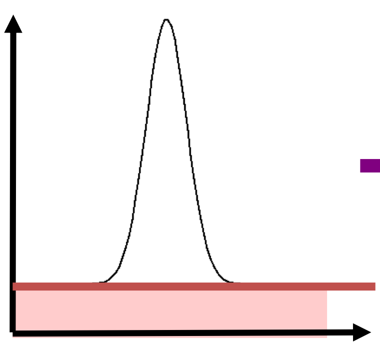




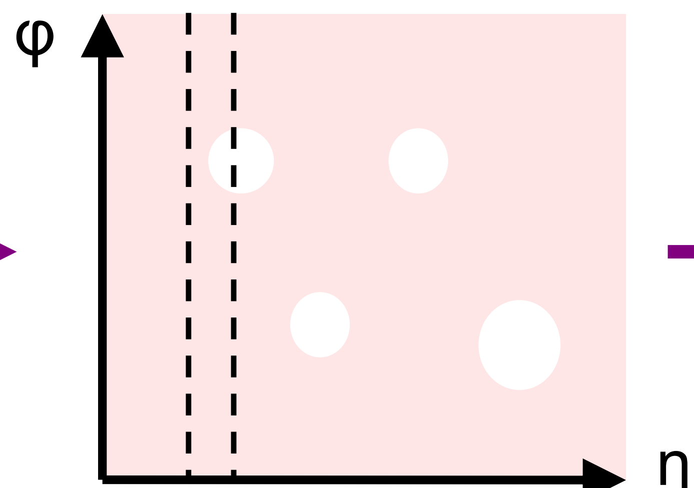
1. Background energy per tower calculated in strips of η. Pedestal subtraction



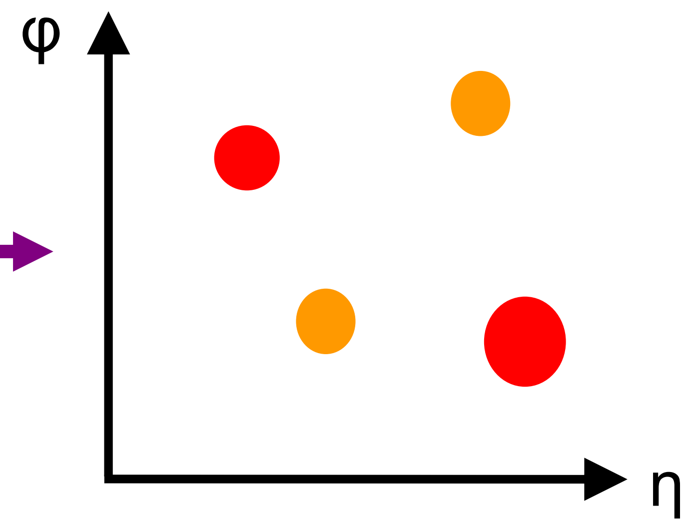
2. Run anti k_T algorithm on background subtracted towers



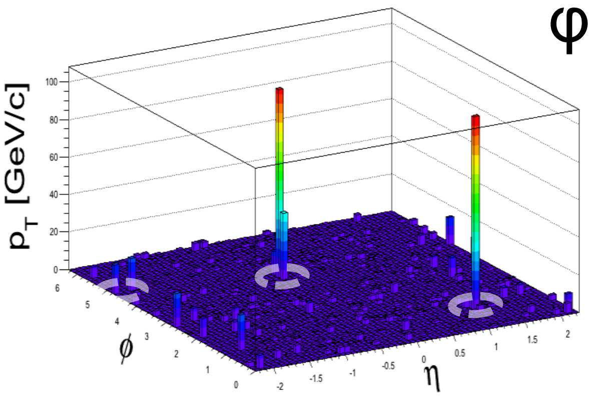
Background level

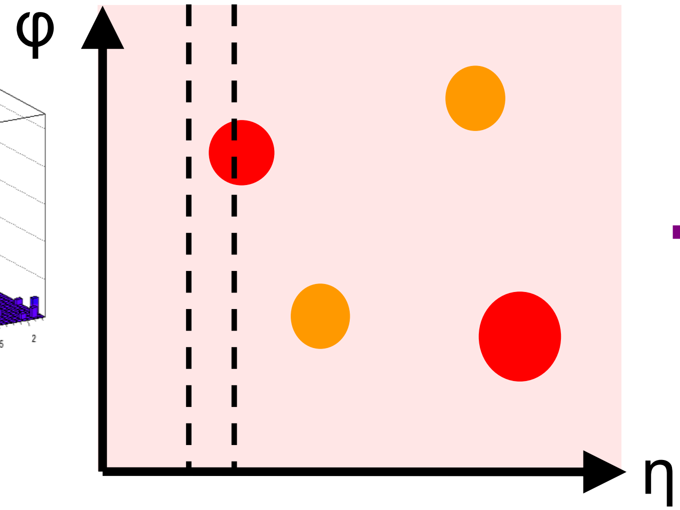


3. Exclude reconstructed jets
Recalculate the background energy

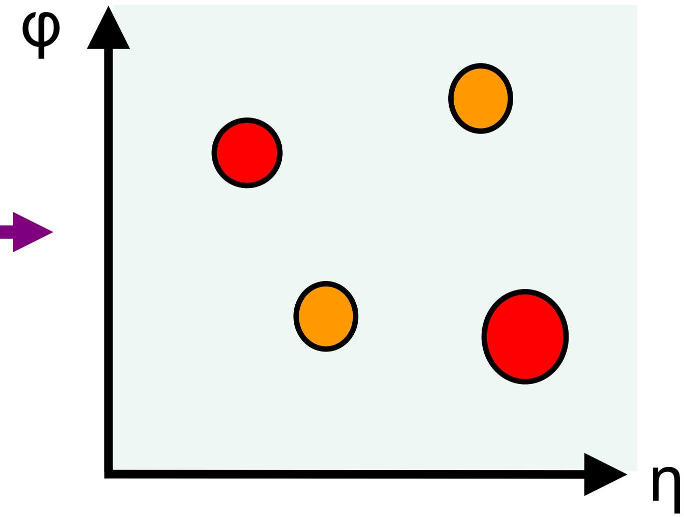


Background Subtraction

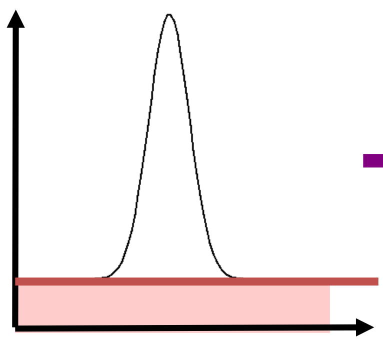




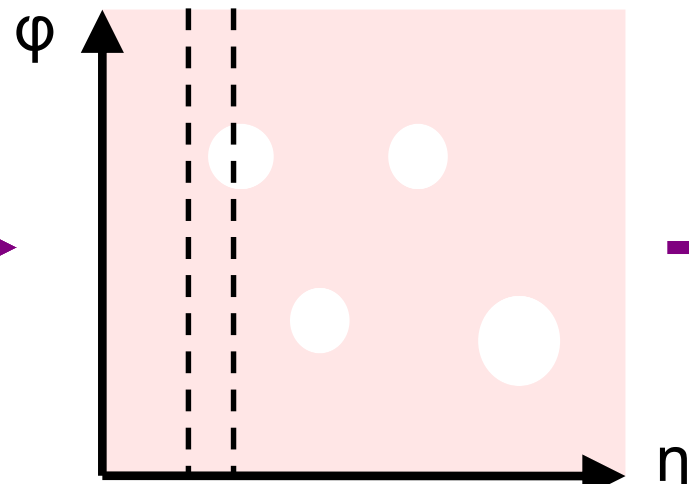
1. Background energy per tower calculated in strips of η. Pedestal subtraction



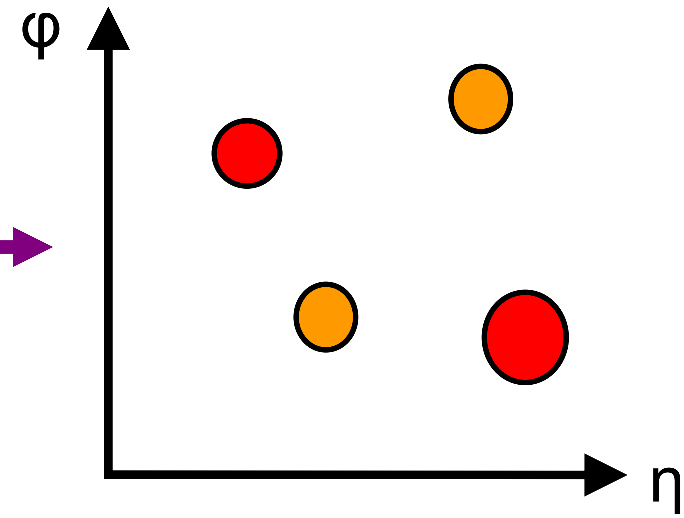
2. Run anti k_T algorithm on background subtracted towers



Background level

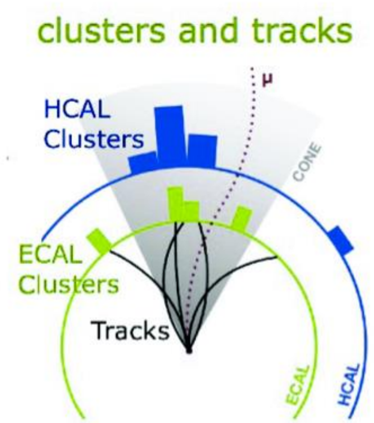


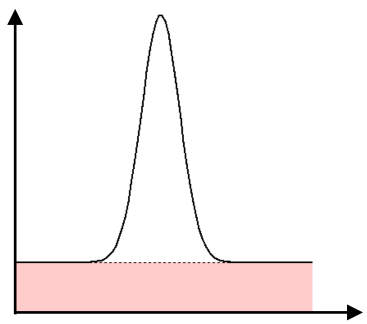
3. Exclude reconstructed jets
Recalculate the background energy

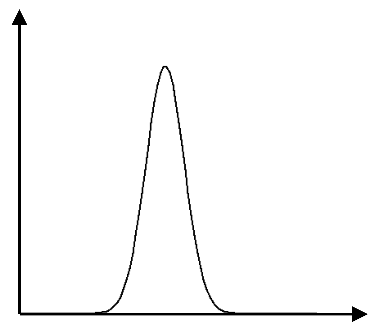


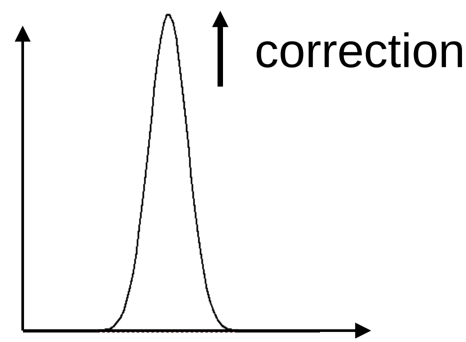
4. Run anti k_T algorithm on background subtracted towers to get final jets

Summary of Jet Reconstruction









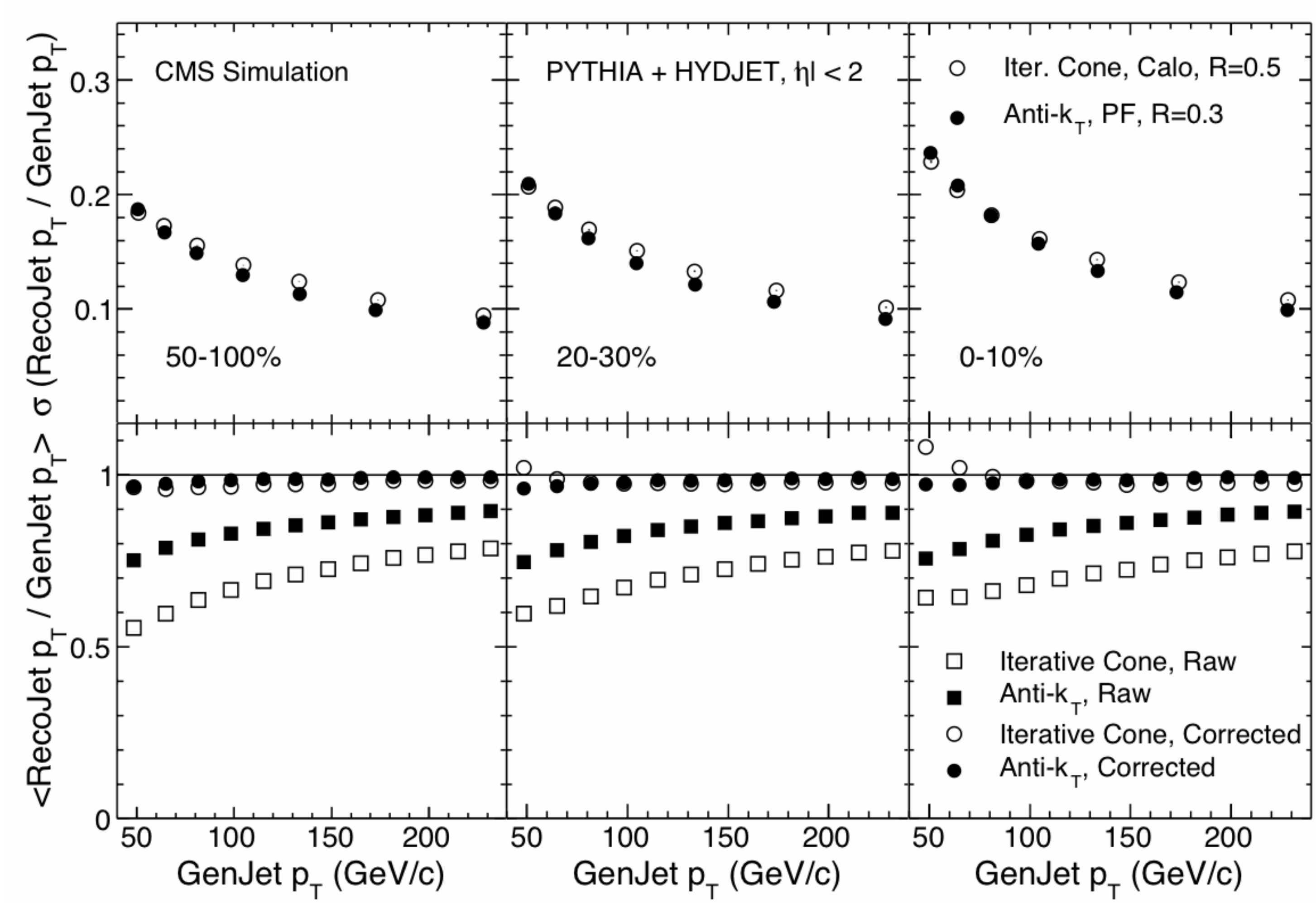
Raw jet energy → Background subtraction → Jet energy correction → Jet energy

Background subtraction: Remove underlying events contribution

Jet energy correction: MC Simulation PYTHIA

PF Jet Performance in PbPb

Resolution: PF jet performance similar to calorimeter jets
Competing effects: Better energy resolution of constituents, but increased in/out-of-jet migration due to smaller R

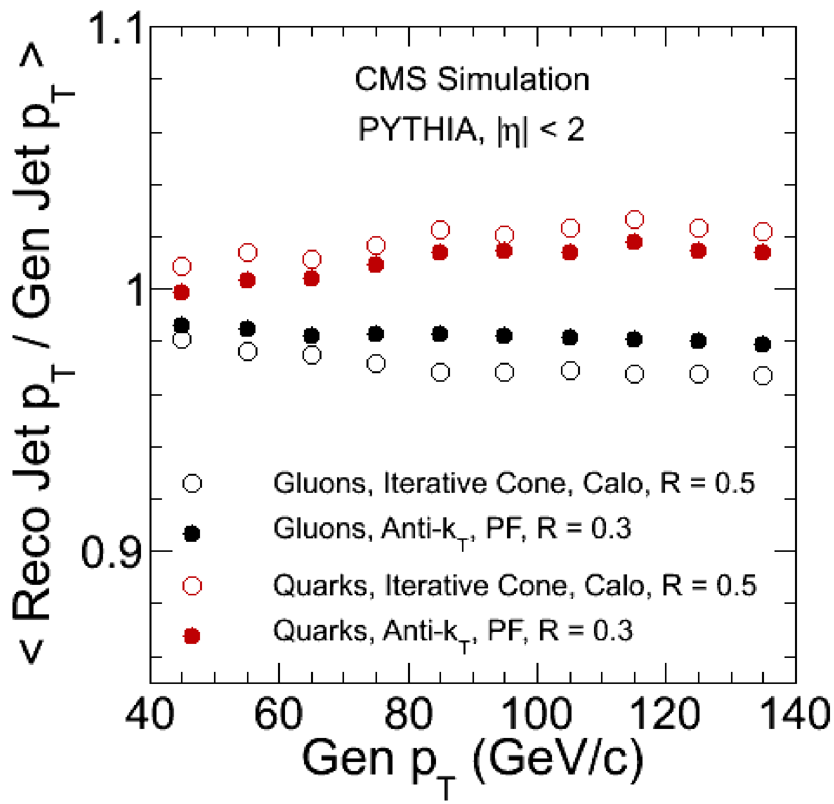


Raw response: closer to unity for PF → reduced uncertainty due to JES
Corrected response: good closure → PF robust against multiplicity

Sensitivity of Energy Scale to the FF

- Jet energy corrections are derived from inclusive jets in PYTHIA
- In real data response may differ due to:
  - Poor description of fragmentation
  - Different fraction of quark vs gluons
  - Possible jet quenching effects

Corrected response to quark and gluon jets

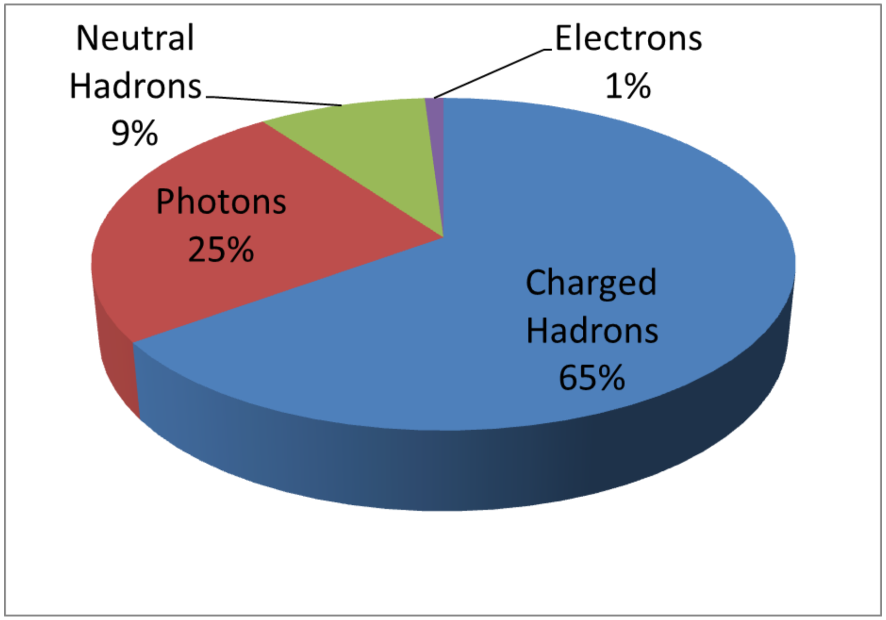


Using PF heavy-ion configuration

Particle flow jets show reduced sensitivity to the fragmentation pattern

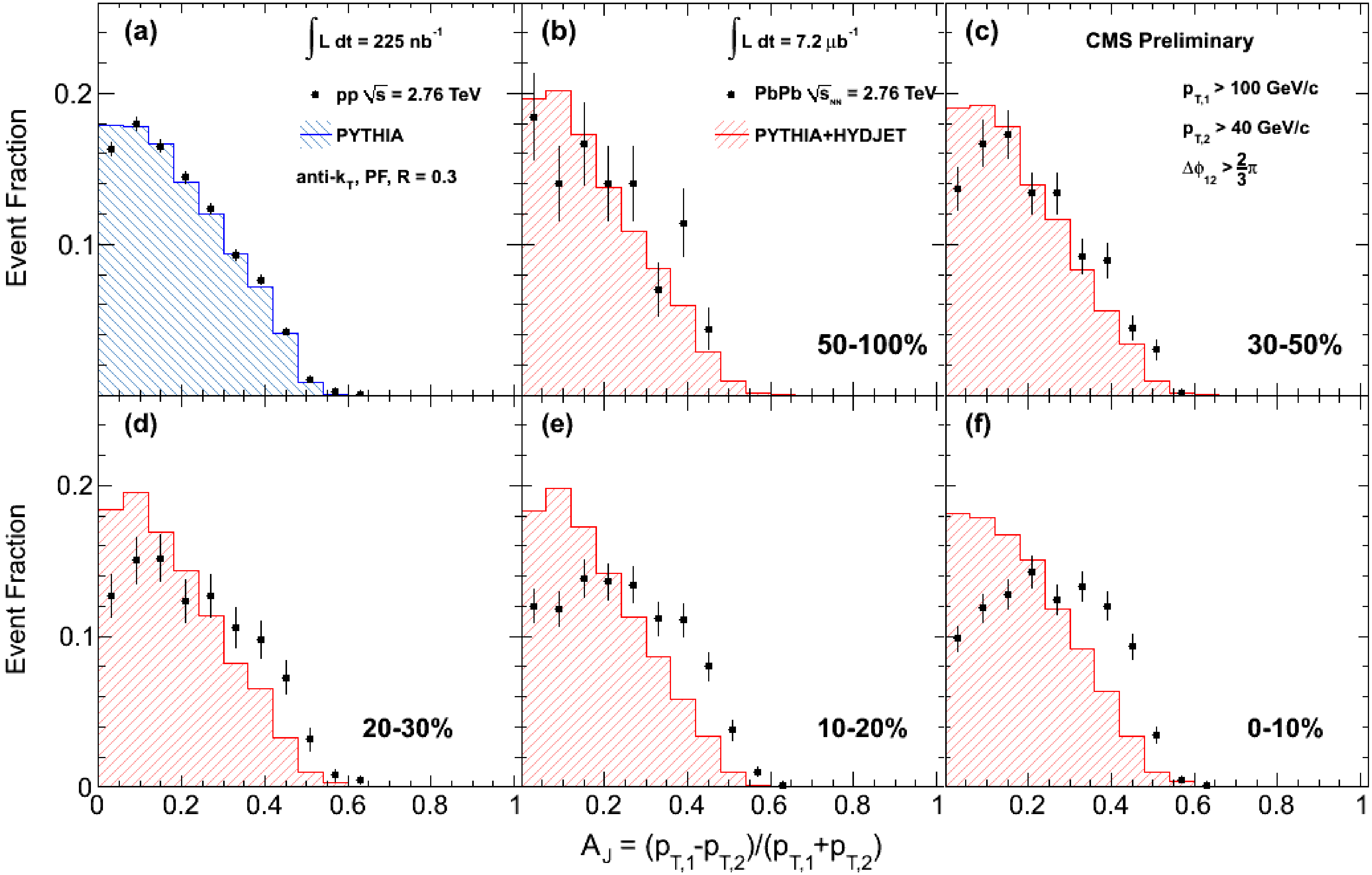
What do we expect with sPHENIX

	CMS	ALEPH	ATLAS	sPHENIX
Magnetic field	3.8 T	1.5 T	2 T	1.5 T
Lever arm	1.29 m	1.8 m	1.4 m	-
Bending power	4.9 Tm	2.7 T.m	2.8 Tm	-
Pion reconstruction efficiency ($p_T = 5$ GeV)	90-95%	99%	90-95%	95%
Tracker thickness at $\eta = 0$ (λ_I)	0.35	0.02	0.4	-
ECAL Molière radius	2.2 cm	1.6 cm	4.0 cm	-
ECAL granularity	0.017×0.017	0.015×0.015	0.025×0.025	0.025x0.025
ECAL resolution	$\frac{3\%}{\sqrt{E}} \oplus \frac{12\%}{E} \oplus 0.3\%$	$\frac{18\%}{\sqrt{E}} \oplus 0.9\%$	$\frac{10\%}{\sqrt{E}} \oplus 0.17\%$	$\frac{15\%}{\sqrt{E}}$
ECAL longitudinal segmentation	no	yes	yes	-
HCAL granularity	0.085×0.085	0.06×0.06	0.1×0.1	0.1x0.1
HCAL resolution	$\frac{110\%}{\sqrt{E}} \oplus 9\%$	$\frac{85\%}{\sqrt{E}}$	$\frac{55\%}{\sqrt{E}} \oplus 6\%$	$\frac{120\%}{\sqrt{E}}$



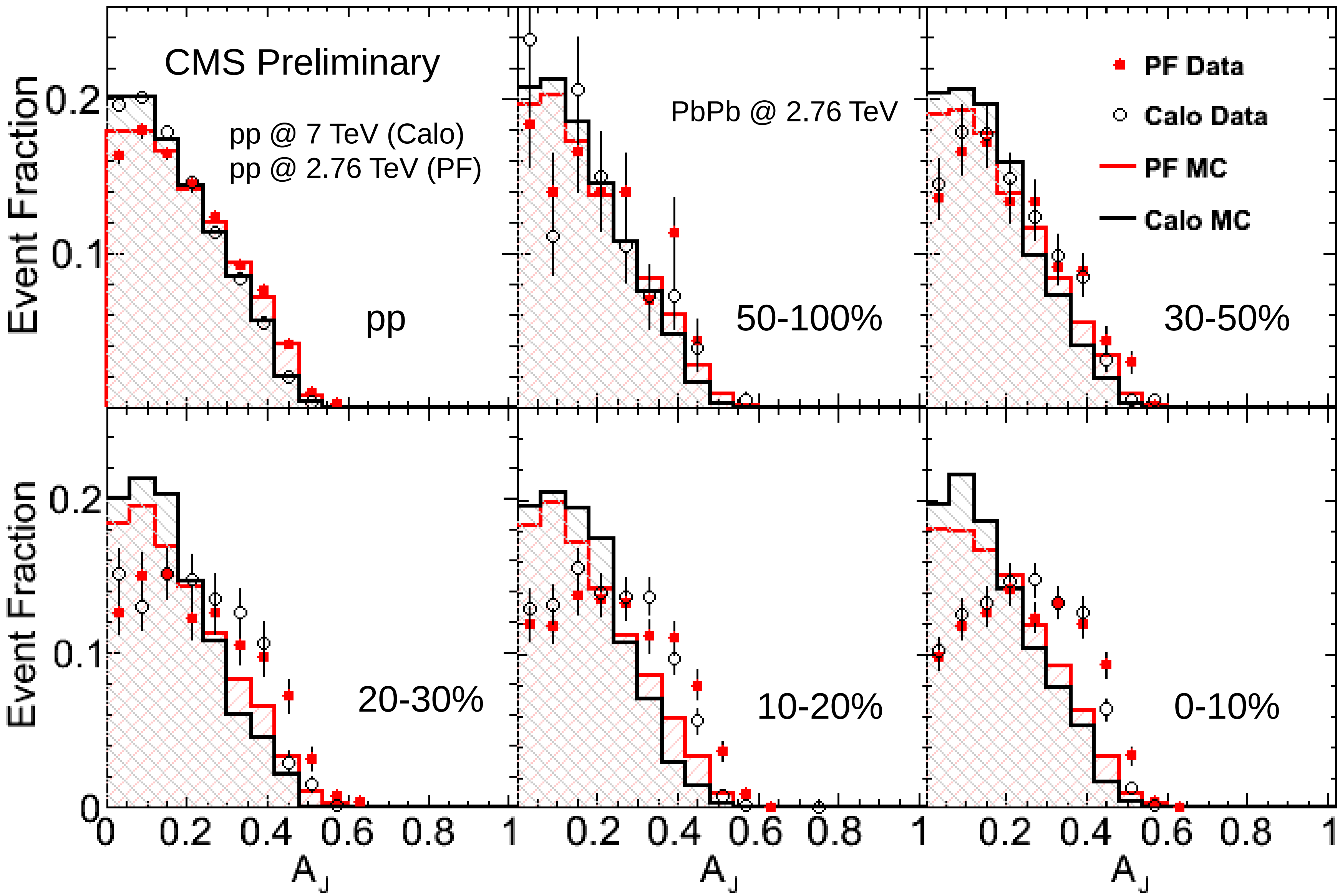
Backup

Dijet Imbalance for PF Jets



Excess of unbalanced jets persists with PF, R=0.3 dijet selection

Comparison to Calorimeter Jet Imbalance



Results are in good agreement with previous calorimeter measurement

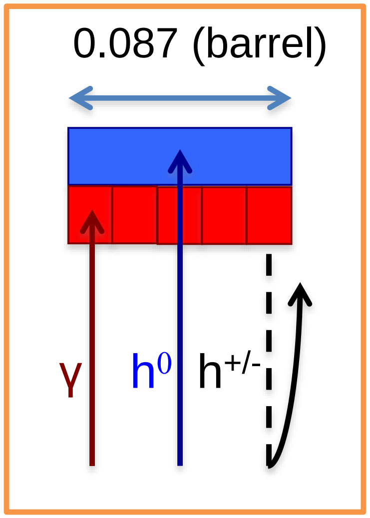
Summary

- Particle flow event reconstruction has been applied in PbPb collisions for the 1st time
- Jets reconstructed with particle flow show good performance in heavy ions in terms of
  - High efficiency for low p_T jet reconstruction
  - Low rate of mismatched dijets
  - Small sensitivity to the fragmentation pattern of jets
- Particle flow jet reconstruction facilitates the measurement of the fragmentation function

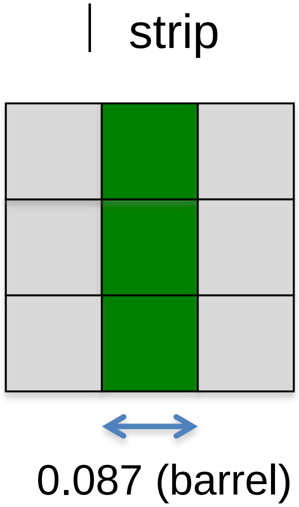
  → See talk by Yetkin Yilmaz in the next session

Background Subtraction

PF pseudo-tower



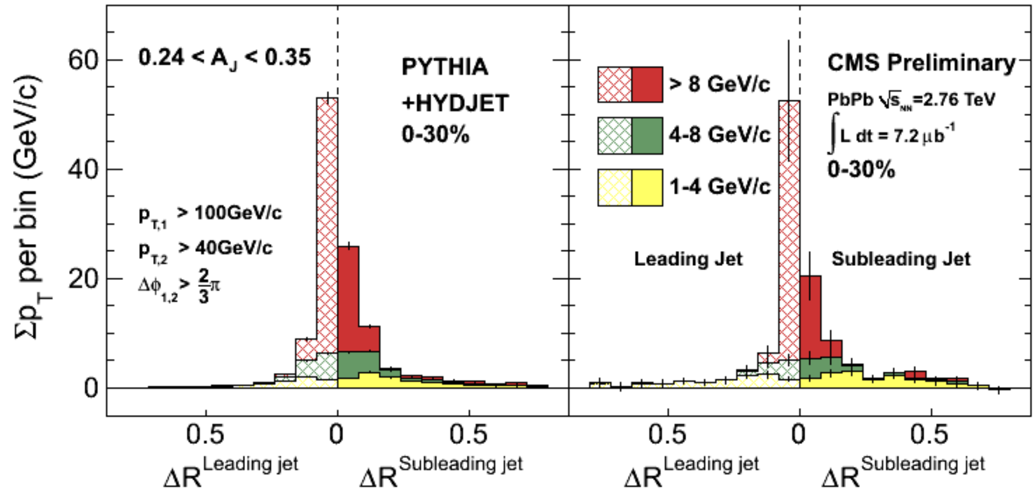
- Reconstructed particles towered into an (η,φ) grid according to HCAL cell dimensions
- Mean tower energy and dispersion are calculated for each η strip
- Same iterative background subtraction applied in [0], described in [1]
- Random cone studies show good agreement between background fluctuations in data and HYDJET simulations
- The effect of quenching on the energy scale is constrained using the jet associated charged particle spectra



[0] CMS, arXiv:1102.1957
[1] Kodolova et al., EPJC 50 (2007) 117

Dijet Analysis with PF Jets

Jet-Track Correlations



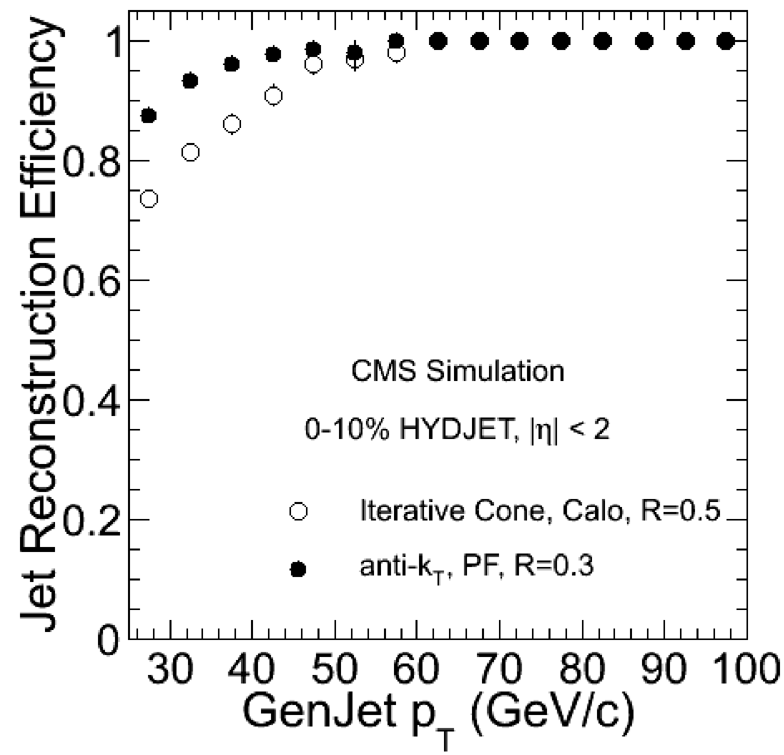
- Jet-track correlations suggest hard fragmentation looks “vacuum-like”

  See: CMS, arXiv:1102.1957

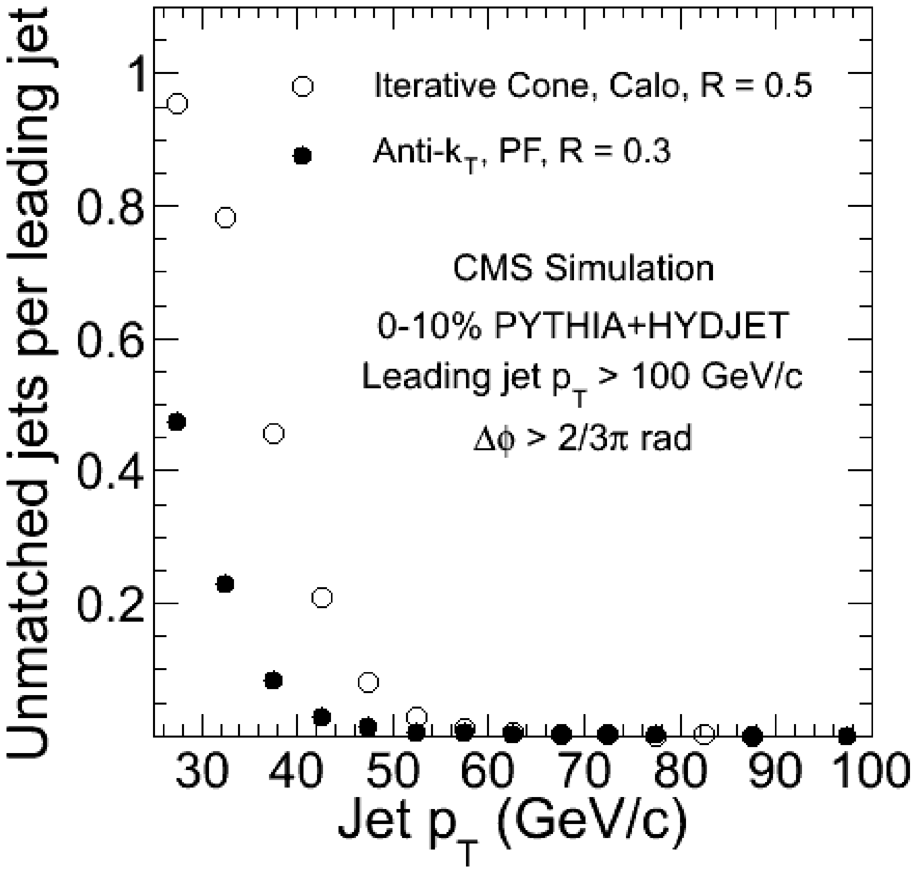
- Fragmentation analysis: Focus on core of jets using anti-k_T PF jets with R = 0.3

  Talk by Yilmaz, next session

- This jet definition is nearly fully efficient down to p_T of ~ 40 GeV/c



Dijet "Mismatch" Rate



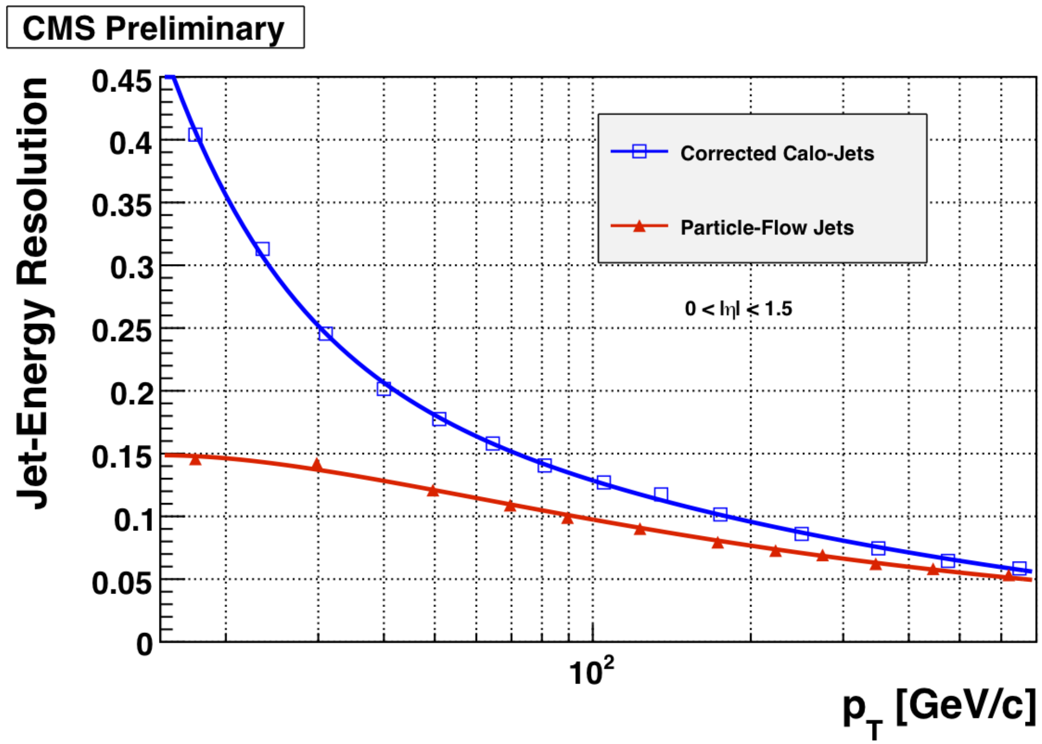
- Embed PYTHIA dijets in a heavy-ion background (HYDJET)
- Require leading jet p_T > 100 GeV/c
- How often is an away-side jet not the true dijet partner?
- Count **all** away-jets per leading jet which do not match to PYTHIA jet

Low rate of mismatched jets at 40 GeV/c with PF jets using R=0.3

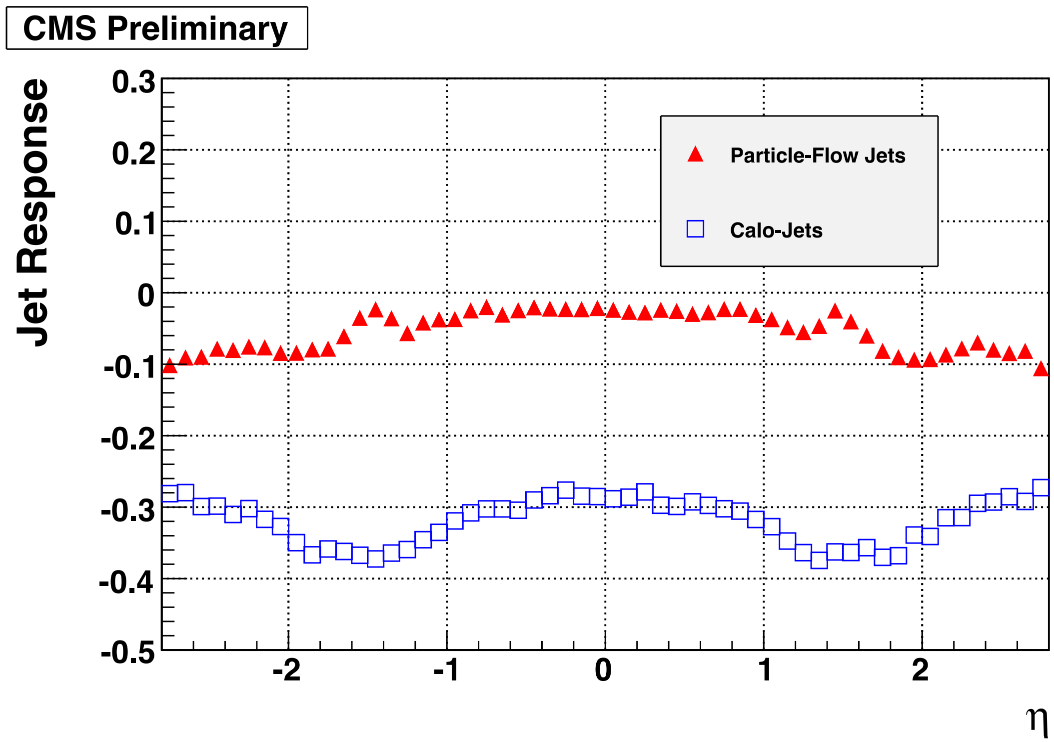
Acknowledgement

Special thanks to Colin Bernet, Patrick Janot and the rest of the Particle-Flow Physics Object Group

Jet Resolution in pp



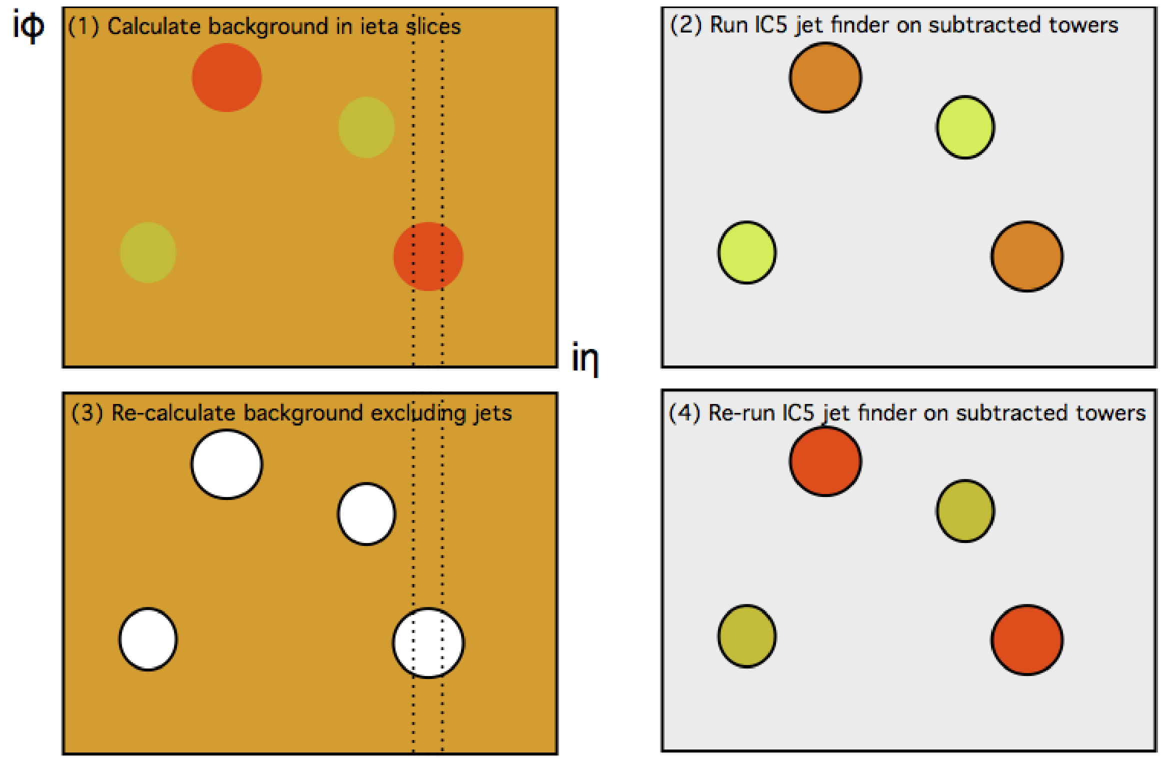
Jet Response vs η



Somewhat lower response in endcaps due to increased material budget / lower tracking efficiency

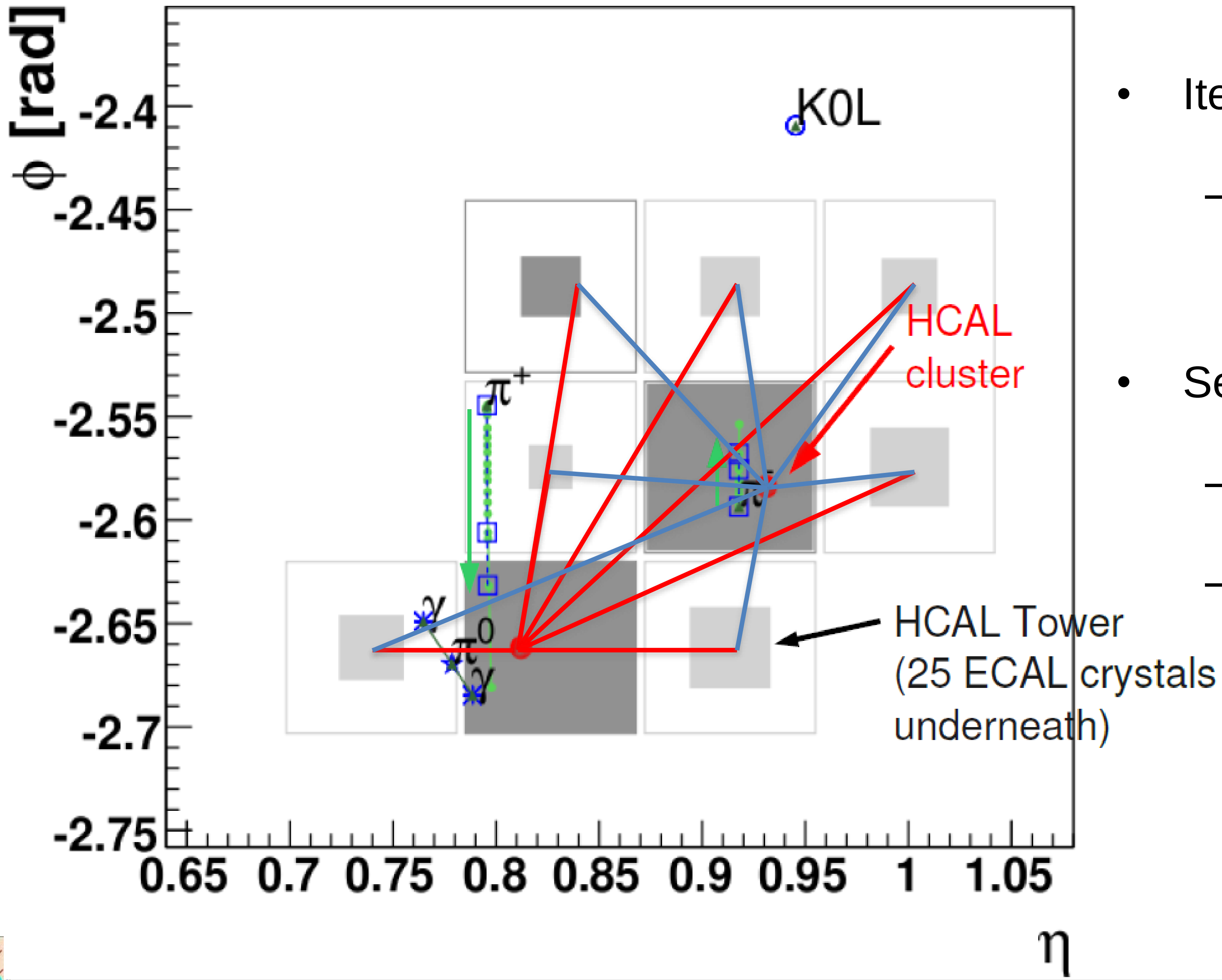
Background Subtraction

1. Background energy per tower calculated in strips of | .
2. Iterative Cone (R=0.5) algorithm run on subtracted towers
3. Background energy recalculated excluding jets
4. Jet algorithm rerun on background subtracted towers, now excluding jets, to obtain final jets



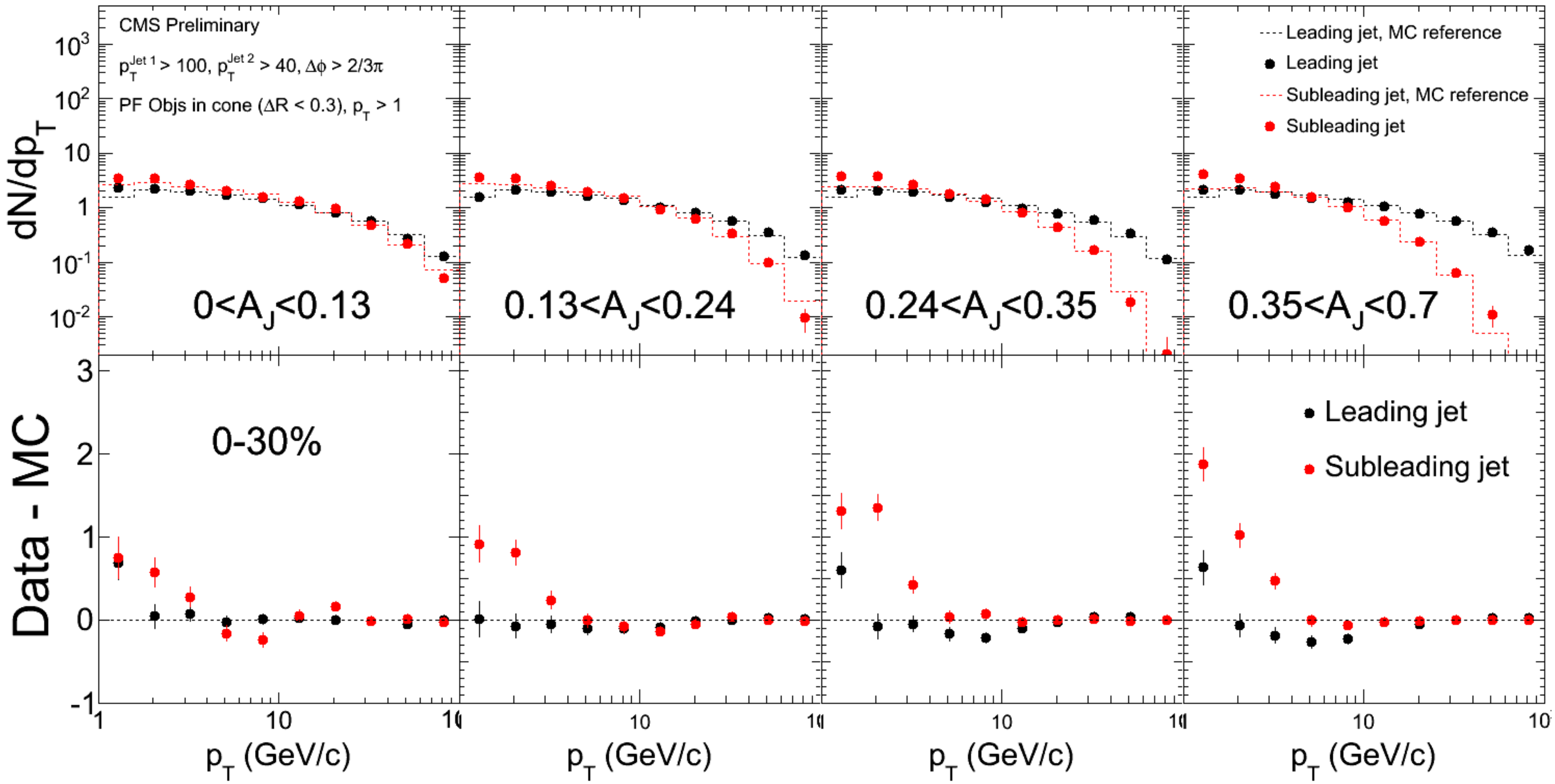
O. Kodolova et al., EPJC (2007) 117.

PF Calorimeter Clustering

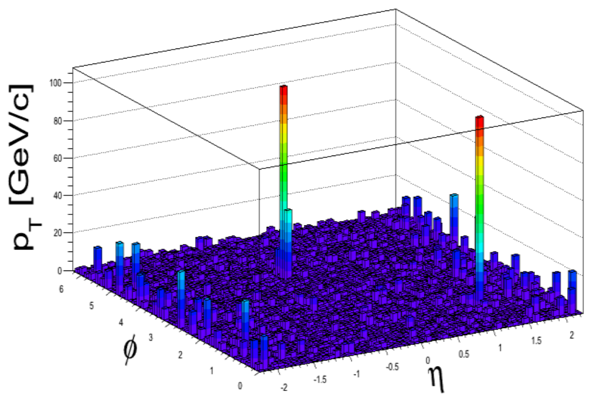


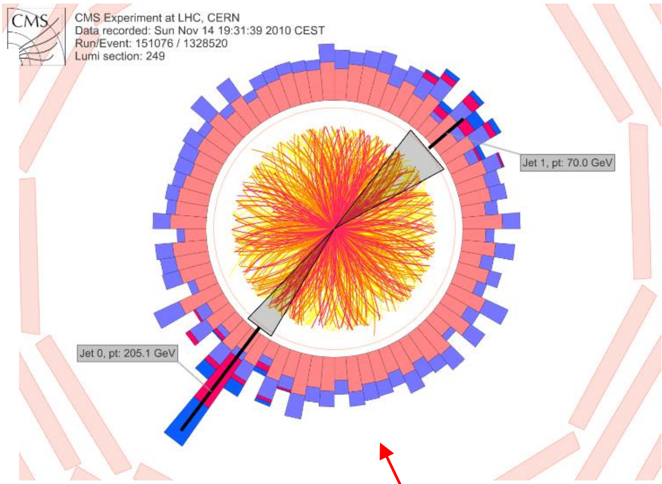
- Iterative, energy sharing
  - Gaussian shower profile with fixed σ
- Seed thresholds
  - ECAL: E > 0.23 GeV
  - HCAL: E > 0.8 GeV

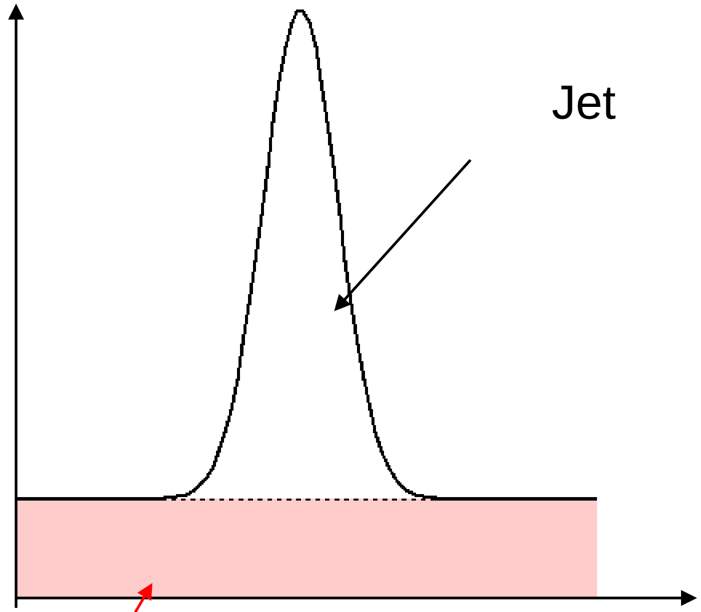
Residual Energy in the Cone



Underlying Event Background







Multiple parton interaction

Large underlying event from soft scattering

Need background subtraction